



Active Thermography for Non-invasive Inspection of an Artwork on Poplar Panel: Novel Approach Using Principal Component Thermography and Absolute Thermal Contrast

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Abstract

The conservation of the works of art represent a topic of global interest. The development of effective tools based on advanced technology for analysing and monitoring their health-state is essential to assuring their preservation. In fact, detecting and preventing the formation of defective areas or assessing for an accurate pre-restoration analysis are the main objectives of non-destructive inspection. Active thermography is a well-known non-invasive imaging technique and reliable tool for providing a fast and low-cost analysis of a work of art. In this study we combine the potential of Principal Component Thermography and of Absolute Thermal Contrast to analyse thermal images acquired in-situ on a poplar panel painting representing an original artwork dating in the end of XVI century. We first optimized the thermal stimulation parameters in the laboratory using special phantom samples. These samples were specially made by reproducing in high fidelity the structural properties and materials of the artwork in order to perform effectively the preliminary tests. Then we moved the equipment in-situ by performing the non-destructive inspection directly on the real artwork. We have developed a specific experimental protocol that combines active thermography with two specific and appropriate image processing modalities that allowed us the effective detection of various types of defects in the painting layer. We report a complete analysis and deep discussion concerning the detection and characterization of the defects. Results show that our diagnostic protocol is a powerful tool in assessing the pre-restoration health-state and suitable for in situ analysis of wood artworks.

Keywords Active thermography · Principal component thermography · Absolute thermal contrast · Artwork · Non-invasive analysis

1 Introduction

In the last decades there has been a growing of renewed interest in the conservation of work of art belonging cultural heritage. Even more innovative and effective inspection tools as well as new investigation analysis protocols are demanded for their protection and restoration [1–10]. In the case of painting on wood, various factors can affect its

integrity such as for example fluctuations in environmental parameters (e.g. temperature and humidity), the presence of atmospheric pollutants, exposure to inappropriate light or the formation of bacterial biofilm [11–16]. Deterioration processes can become irreversible with time and therefore it is important to detect and prevent their formation as soon as possible using non-destructive investigation methods. In this context, high-tech, powerful, non-invasive and innovative tools, based on modern advanced technological devices and professional imaging techniques, can play a crucial role. For panel painting inspection, several diagnostic techniques have been used but most of these are difficult to apply in situ mainly because of high costs and the strict stability conditions required. Active thermography (AT) is a well-known contact-less and non-invasive imaging technique [17–26]. It is fast and of easy implementation and it represents a reliable means of providing a low-cost in situ analysis of an

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artwork [27–36]. According to this technique, the surface of the object under investigation is stimulated using an external heat source to produce a dynamic thermal response that can be detected and recorded with an infrared camera. AT allows a rapid detection of a wide variety of defects such as voids, inclusions, delaminations, cracks, detachments, presence of nails and any type of anomaly that determines a change in thermo-physical properties of the painting under investigation. Due to its abundance in central and southern Europe, poplar has been the most commonly used wood in many Italian early Renaissance paintings and in various works of art by famous European artists. Many works by artists such as Dürer, Rembrandt, 41 panel paintings (on a total of 47) ascribed to Raphael as well as the most famous painting in the world “Mona Lisa” of Leonardo Da Vinci, just to name a few, are realized on poplar panels [37–39]. Here we report on in situ thermographic analysis of an artwork made on a poplar panel preserved at the University Suor Orsola Benincasa of Naples (Italy) and datable in the last decades of XVI century. At the aim to furnish information on the health-state for a pre-restoration assessment, we developed a new protocol which allowed us detection of defects in the examined artwork, thus demonstrating the usefulness of AT in a specific case-study. In particular, in order to operate in non-invasive condition, the parameters characterizing the thermal stimulation procedure were pre-optimized in laboratory using panel phantom samples specially made for this occasion. The phantom’s sample replicate as much as possible the physical and structural characteristics of the original artwork. In literature, many techniques for the analysis of thermal image sequences have been implemented and used [19–21]. However, due to their inherent limitations, none of them alone can fully satisfy the needs that arise in the analysis of a work of art. Here, at the aim to optimize our understanding of the data acquired, we use a combination of Principal Component Thermography (PCT) and Absolute Thermal Contrast (ATC) methods to analyse the thermal images in spatial and temporal dimensions. PCT is based on a statistical analysis and it provides a compact representation of the acquired data by condensing the main spatial and temporal variations into a few images [40–43]. ATC method provides the specific time domain behaviour of areas that appear inhomogeneous to the PCT analysis, allowing their diversification and an attempt at classification. Combining the potentiality of these two methods of analysis, we highlighted the presence of different type of defects and anomalies in the painting layers making assumptions and hence providing important pre-restoration information. Our results confirm that AT is an effective tool for the in-situ analysis of paintings on wood, especially if the stimulation protocols are optimized ad hoc and if the acquired thermal images are analysed combining multiple techniques that provide complementary results.

2 Materials and Methods

2.1 Active Thermography Measurements

AT measurements were carried out in order to identify the presence of defects and anomalies within the painting examined. They were performed using a halogen lamp with tunable power as heat source to apply a thermal pulse of the order of seconds on each investigated area. The thermal response achieved during and after heating was recorded with a frame rate of 10 Hz using a MWIR camera FLIR X6580 sc with a cooled indium antimonide (InSb) detector (spectral range 1.5–5.4 μm , FPA 640 \times 512 pixels and NETD \sim 20 mK at 25 $^{\circ}\text{C}$) mounting a 50 mm focal lens with spectral band 3.5–5 μm and IFOV 0.3 mrad. The commercial software ResearchIR (FLIR Systems), with which the camera is supplied, is used for monitoring the temperature in real-time and for basic operations. The illuminance on the samples was measured using a photoradiometer (Delta Ohm HD 2102.2) with a lux meter probe (LP 471 PHOT). In Fig. 1a is shown a scheme of the experimental set-up used while in Fig. 1b and c two photos respectively in laboratory and in-situ.

2.2 Artwork Investigated

The artwork analysed in-situ is an oil painting realized on a supporting structure in wood of dimensions 89 cm \times 111.5 cm \times 3 cm. It is a representation of the Eternal Father of an unknown author (Fig. 2a). Its stylistic analysis leads to placing the work in the in the end of XVI century. The wood was attributed to a species of poplar (*Populus* sp.) according to characters useful for wood determination. The colours used by the artist are, on the chemical elements, for the yellows, browns and reds characterized by the earths on iron oxides, the whites on white lead, some reds (especially the lips and fingers) cinnabar/vermilion, while blues and greens have a copper-based composition (possible carbonates).

2.3 Phantom panel Painting Samples

Preliminary to the analysis of the artwork, the parameters concerning the thermal stimulation were optimized in laboratory using panel paintings on poplar support (dimensions 20 cm \times 20 cm \times 3 cm, Fig. 2b) made with preparations techniques, structure of the layers (Fig. 2c) and pigments similar to those of the original artwork deduced from a precedent X-ray fluorescence (XRF) analysis (see supplementary material).

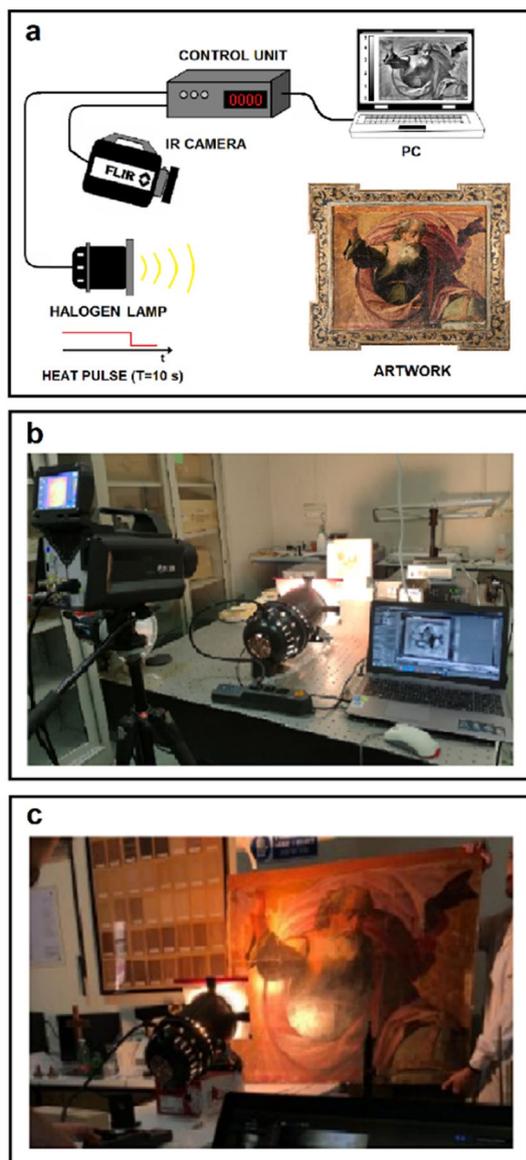


Fig. 1 Experimental set-up: a scheme of the set-up, photos realized in b laboratory and c in-situ during the thermal measurements

2.4 PCA and ATC for Spatial and Temporal Analysis

The sequences of thermal images recorded have been processed by both PCT and ATC methods. PCT is a statistical analysis useful to produce highly compact representation of the thermal variations associated with structural defect. A pre-processing phase is needed to organize the thermal data in a convenient way for the analysis. The sequence of n_t thermal images of $n_x \times n_y$ pixels is reduced by a raster-like operation in a two-dimensional matrix M of dimensions $n \times m$ with $n = n_t$ and $m = n_x \times n_y$ where each column represents the temporal evolution of a single pixel and in each row is condensed a single image of the sequence (spatial variation). A standardization

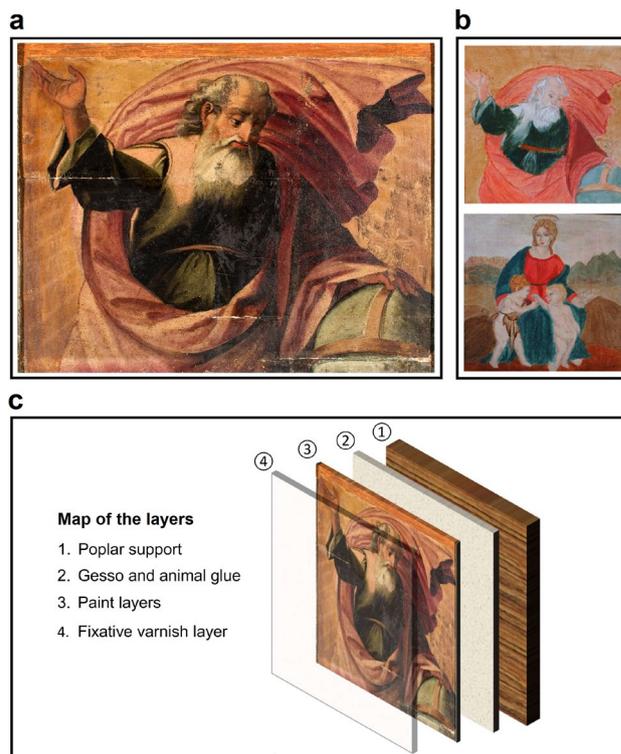


Fig. 2 Samples analysed: a image of the artwork analysed in-situ, b images of the panel painting samples specially made analysed in laboratory, c map of the layers of the painting

procedure is then applied on the column vectors of M to normalize the data with respect the pixel to pixel variation in the acquisition of the detector è [42]:

$$M_N = \frac{M(n, m) - \mu_m}{\sigma_m}$$

$$M_N = \frac{M(x, y) - \mu_y}{\sigma_y}$$

where

$$\mu_y = \frac{1}{n} \sum_{x=1}^n M(x, y)$$

and

$$\sigma_y^2 = \frac{1}{n-1} \sum_{x=1}^n (M(x, y) - \mu_y)^2$$

Successively, singular value decomposition (SVD) is used to reduce the normalized matrix M_N achieved to a highly compact statistical representation as follows:

$$M_N = UVS^T$$

In the last equation, V is a diagonal matrix $n \times n$ where the elements represent the eigenvalues of M_N in descending order. U is a matrix $m \times n$ where the column represents a set of empirical orthogonal functions (EOF) that describe spatial variations in the data. S is a matrix $n \times n$ where the column are vectors named principal components (PCs) that represent the time behavior of the EOF.

Resizing the columns of U of dimension $m \times 1$ in two-dimensional $n_x \times n_y$ matrices, we achieve new images named spatial components (SCs) that can be visualized and analyzed.

To classify the inhomogeneous areas found by PCT analysis we studied their thermal behaviour by ATC technique. ATC is a simple and fast method that allows to compare the temporal temperature response of different points of the sample under investigation and it represents a relevant parameter for defect detection and characterization. Many classical signal processing techniques used in literature are based on thermal contrast computations, also thanks to the possibility of correlating the time in which the maximum contrast value appears with the size and position of the defect [19]. Here, we analyze and compare the characteristic thermal response shown by the various defects present in the painting in order to make a tentative assignment of their nature. In particular, on areas of 5×5 pixels in correspondence of an inhomogeneity detected with PCT analysis we calculated the thermal contrast $\Delta T(t) = T_D(t) - T_{sa}(t)$ where $T_D(t)$ is the temperature trend of the defective area and $T_{sa}(t)$ that of a sound area appropriately chosen.

In our evaluations, we have identified as 'sound' an area that having the following requirements: (a) located as close as possible to the defective one, (b) of the same colour as the defective one and (c) that did not differ in the trend if compared with another possible sound area chosen in the same way, practically, the trend $\Delta T(t) = T_{SA1}(t) - T_{SA2}(t)$ have to be in proximity of zero (x axis).

The calculation with both PCT and ATC methods were performed by the use of home-made Matlab (R2019a, MathWorks) codes. To process the sequences of thermal images, we used a computer with an Intel processor i7-4770 CPU @ 3.40 GHz with 8 Core and 32 Gb of RAM.

3 Results and Discussion

In the analysis of most work of art, the application of models and methods based on ideal assumptions, such as uniform and flat surface of the sample, it is somewhat risky and ineffective. In most cases, the structure of the layers of a painting is not completely known and the surface is not perfectly flat. Furthermore, the lack of data on the thermal/optical properties of the artistic materials leads to strong uncertainties concerning the interaction between the thermal waves of the

external source and the sample under examination. Given these circumstances, for the analysis of an artwork it is convenient and appropriate to make use of methods that are not based on specific assumptions and that are well suited to the description of each experimental situation. Among such methods, PCT appears to have appropriate characteristics. PCT is a more universal approach in which no assumptions are made about the properties, composition or geometry of the sample under investigation and, as well known, it is independent of any physical model. Thanks to these properties the PCT can be considered one of the most promising and interesting methods for the analysis of artwork. More than 85% of the variance present in the set of thermal images analyzed is represented (in descending order) in the first three spatial components (SC), calculable with this technique, that, substantially, contain most of the structural information [40, 44]. The others SC calculated contain only electronic and thermal noise and can be neglected. The first SC is an image that represents the non-uniformity heating due, for example, to a different heat absorption or emissivity of the paint colors while the variations in the second and third SC can be directly associated to inhomogeneities and defects in the painting layers and in the subsurface structure. In the second SC are visible defective areas characterized by higher thermal variations compared to those visible in the third SC. Therefore, the defects visible in the second SC are those generally present in the surface layers of the painting or characterized by higher thermal conductivity. Vice versa, in the third SC only those defects that afflict the deeper layers of the painting or the minor superficial ones are visible. In order to study the nature of the inhomogeneities found is essential to investigate about their geometry and, more important, their temporal behavior. Unfortunately, an important limitation of the PCT is that it only allows an evaluation of the average temporal response relative to the whole image [44, 45]. Consequently, this method cannot provide information relating to the temporal behavior of each suspected defective area found in the SCs and therefore allows neither to assign a nature to defects nor to the differentiate ones. In addition, the orthogonal base on which the SCs are calculated is built independently in each individual analysis and therefore it differs from one area of the painting to the other investigated. As a consequence, the same type of defect can appear with a light or dark colour when considering SCs of different areas of the painting. Hence, to classify correctly the inhomogeneous areas found with PCT analysis we have studied their temporal response by ATC method (as described in the Sect. 2.3), a natural approach currently used in active thermal NDT based on the analysis of differences in time evolution of defect and sound areas.

Here, we discuss a combination of these two methods in the analysis of the artwork. Preliminarily, the protocol for the thermal stimulation was optimized for a non-invasive

analysis performing measurements in laboratory on painting samples specially prepared. As optimized parameters, we mean a suitable setting that allows to get: (1) a heating as homogeneous as possible of the investigated area and (2) a thermal excitation such to induce for the higher emissivity colours a maximum temperature increasing (ΔT_{\max}) of 3 °C (safety limit) and, at the same time, for the lower emissivity colours a minimum temperature increasing (ΔT_{\min}) of 1 °C necessary to perform their inspection. After several tests, performed changing the parameters values, we selected as optimal setting: a pulse time for the thermal stimulation of 10 s, an illuminance of 400 lx and a distance between lamp and artwork of 65 cm. Using these parameters, we performed the thermal analysis on the artwork in situ. We divided the artwork in 9 areas of investigation of dimension of about 30 cm \times 37 cm and we applied the stimulation protocol on each of it. During heating of the 9 areas, using the software supplied with the infrared camera, we checked in real time that the safety limit of $\Delta T_{\max} = 3$ °C was never exceeded. We point out that the total exposure delivered by the halogen lamp in our analysis of 36×10^3 lx·s (400 lx \times 10 s \times 9 areas) is much lower than both the exposure of about 2.6×10^9 lx·s for which a colour change can be observed in a painting and the daily exposure limit corresponding to about 5.8×10^6 lx·s allowed to the National Gallery of London for flash and lighting [31, 46, 47]. Using the infrared camera, we recorded the behaviour of the different area during and after the thermal excitation. Successively, we analysed the frames achieved using both PCT and ATC methods. We used the second and third SC calculated to detect suspected inhomogeneous areas and then the ATC to analyse their temporal behaviour for a tentative of classification. Using this procedure, the presence of different types of defects present in the painting layer have been clearly highlighted.

At ATC analysis the various defects found show a characteristic thermal response that can help in their identification and assignment. As an example, in Fig. 3 it is shown the second SC image of one of the investigated areas (Fig. 3a) and the $\Delta T(t)$ trend (Fig. 3b) of three different defects A, B

and C visible in the image. The temperature variations were calculated with respect to a sound area of the SCs images carefully chosen, where no defects or inhomogeneities are visible. The faster heating/cooling response of defect A associated with a high thermal conductivity and its well-defined circular geometry suggests the presence of a nail. The slow response of defect B associated with a low thermal conductivity and its irregular geometry suggests the presence of air under the painting layer and so a detachment. The lowest temperature rises with respect to the sound area (negative $\Delta T(t)$) of defect C can be associated with the presence of a smaller quantity of absorbent material (pigments) and therefore with a degraded area with thinner layers of paint.

On this way, all areas of the painting investigated were analysed.

In Fig. 4, it shows the visible images (first column) and the corresponding second and third SC images (second and third columns) of the most significant areas of the painting analysed. A description of the main inhomogeneities identified is here reported.

Figure 4b shows the second SC of an area of the painting where there are two cracks (below A and B) visible also in the picture in Fig. 4a. The crack in A is also clearly visible in the third SC showed in Fig. 4c, indicating how the latter is deep and affects all pictorial layers. Differently, the crack in B is not visible in this SC thus showing a more superficial connotation. In the same area of the painting both SCs show the presence of other two cracks (above C and D) that are not visible to the naked eye, but which are extended and deep. The red boxes E and F in Fig. 4b indicate areas of the panel where the ATC has highlighted in various point of the pictorial layer an initial detachment (white areas) probably caused by the presence of the cracks. In both SCs, on the left of G and H, are well visible some oblique sections of the painting which were practically engraved by the artist on the poplar panel probably in the preparatory phase of the painting.

In Fig. 4e and f a crack is visible (below A, also evident in Fig. 4d) that extends to the deeper layers of the painting.

Fig. 3 Example of ATC analysis of some defects: **a** second SC image of an area of the artwork, **b** thermal response of three different defects: a nail (red line), a detachment (blue line) and a thinner paint layer (green line) (Color figure online)

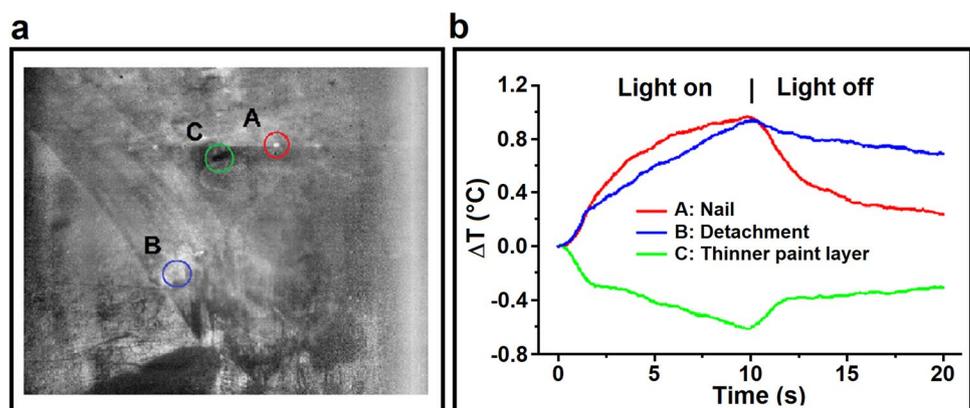
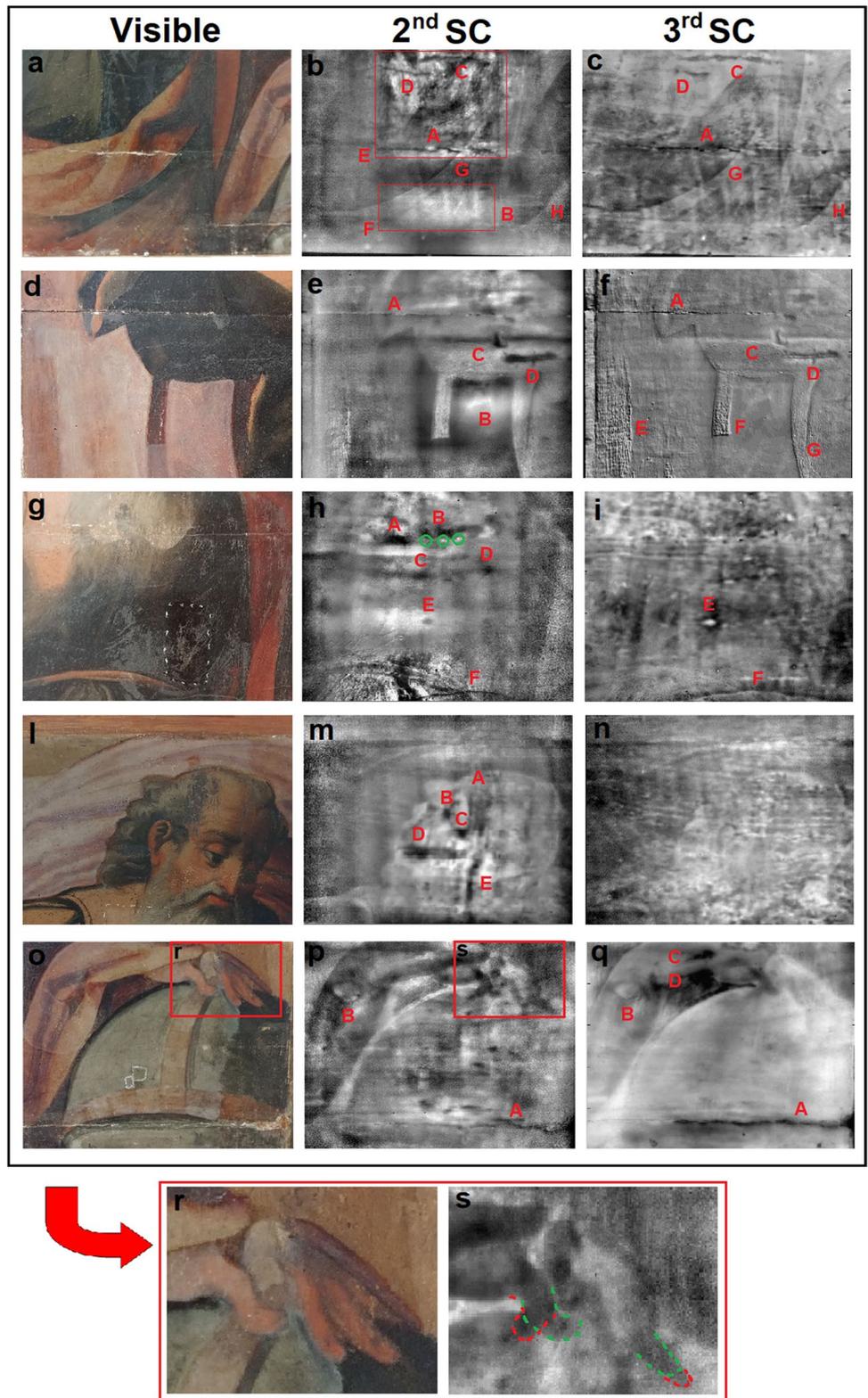


Fig. 4 Visible images (first column) and the corresponding second and third SC images (second and third columns) of the most significant areas of the painting analysed



In Fig. 4e there is a detachment (above B) which, given the shape and size, could be the work of a worm. In both SCs there are also two elongated areas (above C and D) where from the ATC analysis the pictorial layer is thinner. In the

third SC of Fig. 4f also are well visible thicker areas of the pictorial layer probably interested in previous restorations (on the left of E, F and G).

In Fig. 4h, A and B indicate areas in which the ATC analysis shows a lower thickness of the paint. Differently, the areas below C, D and E the same analysis highlights the presence of detachments. In particular, the defective area E (characterized by weaker temperature variations) is clearly visible in the third SC image (Fig. 4i) and it is probably placed in deeper layers of the painting. The three areas circled in green (Fig. 4h) indicate inhomogeneities with a circular shape and diameter of about 1.2 ± 0.2 mm characterized by a high thermal conductivity. They can be associated with the presence of small nails under the pictorial layer. The letter F highlights a deep cracking on the painting visible in both SCs images.

In Fig. 4m there are areas (below A, B, C and D) that are less thick from the ATC analysis where the paint is almost completely detached (clearly visible also in Fig. 4l). On the left of E is visible a dark area where the ATC indicate a probably beginning of detachment. In the same image, a square grid is clearly visible behind the head of the painted subject. Perhaps, they represent preparatory traits created by the artist before painting this essential part of the work. However, the absence of all these inhomogeneities in the third SC (Fig. 4n) indicates that they affect only the surface layers of the painting.

In Fig. 4p and q, A indicates a large and deep subsurface cracking, also partially visible in Fig. 4o, which in its initial part (on the right side) caused the detachment of the pictorial layer. Another subsurface detachment found using the ATC is visible in both SCs images above B. The dark areas on the right of C and D in third SC (Fig. 4q) are in correspondence of two partial detachments that affect a deeper layer of the painting.

In Fig. 4r and s we report the magnification of two small area of the images in the Fig. 4o and p corresponding to the hand of the Eternal Father represented in the painting. Comparing the two images it is possible to notice a *pentimento* of the artist which originally painted the fingers with different positions and size. In Fig. 4s, the green hatch shows the shape of the fingers as present actually in the painting while the red hatch indicates the initial shape of the fingers subsequently modified by the artist.

Here, we do observe, the presence of defects in a very superficial area of the painting and its structural nature as a multilayer (see Fig. 2c) made the use of approaches based on a normalized thermal contrast definition (e.g. Differential Absolute Contrast) impractical. We believe that all the information achieved and here reported on the state of the painting can help, simplify and make more efficient the subsequent restoration operations to which the work will be subjected. The results here presented confirm that the AT by combining the use of PCT and ATC methods for image processing represents an effective tool for a non-destructive in situ analysis of panel paintings. Finally, this methodology

can contribute to an accurate analysis of works of art similar to the one analysed, especially if performed in combination with others non-invasive techniques (digital holography, ultrasound, etc.) which provide results that are both complementary and support each other.

4 Conclusions

In this work we have defined and tested a novel protocol for inspection of work of art. In particular, we use a new approach based on the combination of two well-known techniques such as PCT and ATC to analyse the thermal measurements performed with AT on an artwork represented by a painting on a poplar panel. PCT is used to perform the main analysis on the recorded IR image sequences, allowing to detect areas of the painting with possible defects, while, ATC provides the temperature evolution of these areas allowing their diversification and an attempt in defect classification. In our protocol, in order to safeguard the integrity of the artwork and makes the analysis effectively non-invasive, a preliminary investigation on the artwork has been performed to identify the colours used and its structural properties. From this study it was possible to fabricate phantom samples that reproduce the characteristics of the real artwork and that we used in laboratory to optimize the thermal stimulation procedure to be used in-situ on the painting.

The results achieved in this experimental campaign highlights that AT with the combined use of PCT and ATC methods for image processing represents a very suitable tool for a non-invasive inspection allowing to detect defects and thus to assess the health state of an artwork. The adopted protocol resulted to be accurate for in-situ analysis of panel paintings, it can be of great help in the restoration process and it can be extended also to other kind of work of art.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10921-021-00755-z>.

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