Thermal imaging method to visualize a hidden painting thermally excited by far infrared radiations

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ABSTRACT

The diagnosis of hidden painting is a major issue for cultural heritage. In this paper, a non-destructive active infrared thermographic technique was considered to reveal paintings covered by a lime layer. An extended infrared spectral range radiation was used as the excitation source. The external long wave infrared energy source delivered to the surface is then propagated through the material until it encounters a painting zone. Due to several thermal effects, the sample surface then presents non-uniformity patterns. Using a high sensitive infrared camera, the presence of covered pigments can thus be highlighted by the analysis of the non-stationary phenomena. Reconstituted thermal contrast images of mural samples covered by a lime layer are shown.

Key-words: Thermal imaging, Active thermography, Infrared thermography for material analyses, Optical method for cultural heritage investigation, Optical method for hidden paintings detection.

1. INTRODUCTION

The study of frescoes is a key interest for the understanding of our history and the purpose of arts. There are arguments for the existence of numerous extensive hidden areas below the surface of the walls such as churches or old buildings of historical and architectural place. Indeed, numerous frescoes or paintings have been covered by an opacifiant layer for political or religious reasons in history. These kinds of layer are generally made of lime or plaster. Optical techniques are powerful and versatile tools for the diagnosis of works of art. There is several method used to examine the surface of wall in order to locate possible works of art such as frescoes or mosaics. Some are based on the use of ultrasounds to perform a subsurface echography. Some particular materials such as graphite, metallic or dielectric patterns covered by pigments or plaster have been revealed using THz reflectometer.

Infrared methods are often used in non-destructive testing of materials for inspecting or identifying defects using an either passive or active approach. Passive infrared techniques are used to analyze paint canvases in order to find sketches or previous drawings. However, investigating on walls made of plaster is more delicate by using passive infrared thermography since in steady state, there is no thermal gradient at the surface of the studied object that will be related to a paint layer covered by a layer made of plaster or lime for instance. Active infrared methods are often used to inspect materials as a non-destructive approach. Most of these methods are applied to reveal defects inside material structures. The classical active optical method used to probe this kind of layers consists in exciting the surface using photographic flashes for heat pulsed simulation or halogen lamps for periodic heating. At the same time, the thermal response of the thermally excited surface is recorded using a thermographic camera and the amplitude and phase of the surface temperature are then demodulated using specific algorithms.

Due to the non-uniformity of the diffusivity of the defects inside the sample under test, the resulting surface temperature can reveal changes of the material nature inside the sample. But usually the signal variations emitted by the surface can be very small. It depends of the emissivity factor, viewing angle, and the roughness of the surface. The emissivity of materials factor varies with both its temperature and its wavelength. In this study, we used a large surface blackbody at the relatively low temperature of 500°C as a long wave radiation excitation source.
This choice provides several advantages to inspect walls made of plaster. The use of a black body device rather than a high-temperature lamp permits to get a radiation of longer wavelength range. With the kinds of lamps, the emitted radiation is also shorter since it is filtered by the material of its bulb.

Thanks to the relative transparency of the lime layer in the far-infrared domain, the image contrast can then be improved. Nevertheless, the excitation mode is decisive for the reconstitution of the painting image. That is why the non-stationary effects must be studied in order to obtain a better contrast. The transient method principle will be first presented. The experimental setup of the thermographic inspection method will then be presented. Experimental measurements will be presented and discussed. Encouraging reconstituted paintings hidden under a lime layer of about 1mm were obtained with this method. Finally, conclusion and perspective will be presented.

### 2. TRANSIENT THERMOGRAPHY METHOD PRINCIPLE

Transient thermography, which employs pulse surface heating of an examined object combined with an acquisition of a thermography sequence, is a well-known technique to measure defect inside a multilayered material structure. Indeed, heat thermal flaw inside the material induce a thermal contrast in the recorded surface thermograms. Usually, transient thermography is used to estimate the depth of a subsurface defect from the thermal response. This method permits a quantitative thermal estimation from the analysis of a temporal sequence in order to locate regions of anomalies in thickness for instance. In this paper, we propose to use this technique in order to visualize a painting hidden under a lime layer. A radiative heat pulse is used to thermally excite the surface and the subsurface layers of the object of interest for which a hidden paint is supposed to be embedded.

Several thermal effects occur inside the layered sample due to the non-homogeneous thermal diffusion in the sample when it is excited by a finite pulse of radiative heat flux. A schema of the sample excitation is presented in Figure 2 below.

**Classical active methods effects**

Usually, active methods are applied to a sample in order to generate a thermal gradient to be measured. Generally, optical sources like flash lamp, lamp or laser are used to thermally stimulate the surface. The electromagnetic radiations impinging on the sample surface is mainly absorbed by these materials near the surface. Heat transfer inside the materials is then pure conduction. In our case, we used a large surface blackbody source to heat the sample. The heat impinging on the surface sample is then conducted through the lime layer, then through the painting layers which are thermally more conductive. Due to the non-uniformity of the diffusivity, the surface temperature recorded after a propagation delay, reveals changes in the material nature. This surface can be then visualized by using an infrared camera.

**Partial transmission in the lime layer**

The spectral transmission of a lime layer was previously studied to better understand the radiation excitation propagation and to be able to adapt the source wavelength. The measurements are presented in Figure 1. With the use of a Fourier Transform spectrometer coupled to a Globar source and a bolometer cooled at 4K, the transmission measurements of one lime layer (~100 μm) were carried out. The spectral transmission coefficient of the covering material with this FTIR apparatus, in the far infrared domain (20-200 μm range), is presented.

It appears that far infrared (λ>40μm) electromagnetic radiations are partially transmitted by the lime layer. This represents a determinant advantage to reach hidden paintings layers. It is indeed preferable that a part of the source flux directly excites the interface rather than only the lime surface. The more direct excitation expected would permit to obtain a better contrast in temperature at the lime surface. To do so, a far infrared radiation to excite the sample must be used.
Active method using an extended range source (Effects of the transmission of the excitation radiations)

By considering an extended range radiation as the excitation source, another thermal phenomenon is added to the pure conduction described above. The covering materials are semi-transparent in the far infrared domain. This enables a part of the excitation flux to impinge the interface. A schematic diagram represents this relative transmission of the excitation source through the sample in Figure 2. As it was previously measured, the paintings absorption coefficients depend on its pigments. The absorption properties of the pigments generate local heat generation extremum. For instance, if the absorption of the pigment is higher than that of the lime, the absorption of the pigments produces a local temperature rise. In both the front (side of interest) and the back direction of the substrate, this rise induces a conduction flux. The non-uniform temperature field at the interface then generates, by this conduction flux, a resulting non-uniform temperature field on the lime surface. Using a high resolution and high speed infrared camera, this temperature field can accurately be measured. This allows the visualization of the painting contours. Since the absorbance of the covering material is highly reduced in the far infrared domain, this radiative-conductive phenomenon improves the contrast of the thermal imaging signal. Depending on the pigment absorption properties, the combination of both effects might either help improving or affecting the contrast.

The IR camera focused on the sample, detects the radiosity of the lime surface. This flux is composed of the surface emission (represented in thick green) and the environment radiations reflection, mostly emitted from the black body. The component of the reflection on the sample surface overrides the small surface emission radiation. This is inconvenient for our application as the surface effects are not of interest.
3. EXPERIMENTAL SETUP AND PROCEDURE

Experimental setup
A sample reproducing a fresco was realized for the experiment. A photograph of the painting before and after the covering process is provided in Figure 6(a) and (b). A lime mortar (lime, sand and water mix) was preliminary produced to form the substrate of the sample, comparable to an arriccio of about 1.5 cm thickness. A very thin lime layer (lime and water) was then applied as a simple intonaco. The pigments were painted on this lime layer. Red ochre and yellow ochre mixed with linseed oil were used as paint. Ochre was used since ancient times and linseed is generally used as a pigment binder. The transmission properties were also characterized in a previous study. Within the 20-200 µm range, red ochre has a transmission coefficient around 0.3 while yellow ochre transmission coefficient is around 0.8, which represents a substantially different behavior. The painting was dried for several days before being covered by three thin lime layers. The lime was at last sanded to obtain a plane surface. The pattern of the painting has been designed to assess for our method:

- the ability to detect the presence or the absence of a pigment (left side of the pattern)
- the ability to detect the difference between two pigments (right side of the pattern)
- the length resolution limit of a painted line detection

A blackbody was used as the extended range source. Its target is a 15 cm diameter disc, and the regulated temperature could reach 500 °C, which was used for our tests. This source mostly generates radiations from near to far infrared. A metal sheet was also employed to completely obstruct the black body radiations and produce the excitation pulse. To detect the sample surface temperature variations, a high resolution, mid-infrared camera was used. The InSb detectors allow a 1.5 - 5 µm working wavelength. This camera was purchased at CEDIP® and is referenced as Orion. In principle, around ambient temperature, the camera sensibility is 20 mK. The used acquisition frequency was 100 Hz. Elements of the experimental setup can be seen in Figure 3.

![Experimental bench: black body, painting sample, and the infrared camera](http://proceedings.spiedigitallibrary.org/)

Experimental procedure
The purpose of this study is to detect the heterogeneity inside the sample. It must be avoided to detect all surface effects when the source is activated. As described above on Figure 2, the reflection on the sample produces a substantial glare effect which prevents the sensible emission variations to be detected. The acquisition must then be done when the source is obstructed. The sample was excited for a few minutes. The image processing was realizated at the moment the heat pulse was stopped. Figure 4 shows the mean temporal evolution of the radiative flux measured by the pixels of the thermal camera during this moment. As the camera is a focal plane array of detectors, the signal was averaged on numerous pixels focused on the sample. During the excitation, the detectors were saturated due to the high reflection.
The integration time could have been adapted to measure the radiosity, equal to the sum of the sample thermal emission and the sample reflection, but this latter value was not of interest. It was thus chosen to favor the sample emission detection. The integration time was then chosen relatively long to increase the digital levels (DL) of the processed image. The sharp decrease corresponds to the blackbody obstruction, which is not immediate. The slow decrease which occurs after that (from 1.77s) is due to the temperature decrease of the sample, cooled by the ambiance.

The examination of thermographic data for the detection of a hidden painting can be reduced to a temporal analysis of the thermographic sequence. The temporal data processing of the thermal response of the hidden painting sample consists in computing the thermal contrast function. A common form for a thermal contrast function is given by the signal difference with a reference. Here an absolute contrast $C$ is defined as function of the camera signal $S$:

$$C(t) = S(t_{\text{reference}}) - S(t)$$  \hspace{1cm} (1)

This criterion has to be maximized in order to obtain the best thermal contrast image. The time reference is therefore chosen as close as possible as the excitation pulse end ($t_{\text{reference}} = t_{\text{start}}$). Also, in order to suppress some temporal noise, it is preferable to take into account an averaged signal of the camera during image processing. The contrast $C_{t}^{i,j}$ affected to the pixel $(i, j)$ at the time $t$ is defined as follows:

$$C_{t}^{i,j} = \frac{1}{10} \sum_{t_{0}=t_{\text{start}}}^{t+7} S_{t_{0}}^{i,j} - \frac{1}{10} \sum_{t_{0}=t}^{t+7} S_{t_{0}}^{i,j}$$  \hspace{1cm} (2)

Figure 4: Averaged evolution of the camera signal of pixels focused on the sample around the end of the excitation pulse.

4. RESULTS OF THE METHOD ON A PAINTING SAMPLE COVERED BY LIME

Non-processed thermographic images

In order to understand the requirement to process the recorded thermal frames sequence, Figure 5 shows the camera raw data recorded at two different times of the excitation stimulus. The region of interest of the frame is a rectangle of 192x234 pixels. From those images it is possible to see some surface effects, but the painting pattern is invisible.
Experimental results

Figure 6 displays several pictures representing the painting sample to be detected before it was recovered by a layer of lime (a), the sanded sample after the painted pattern was hidden (b) and the processed image computed using the contrast expression of the algorithm previously described (c). This corresponds to the processed contrast field $C_{t=t_{\text{start}}+4s}$ four seconds after the pulse end, in a gray scale. The resulting image shows a good reconstitution of the painting pattern. First, the presence or absence of pigments is clearly revealed, according to the left part of the pattern. What is more noteworthy is the fact that we can distinguish two shades in the right side. It is thus possible to make the difference between two pigments, between the two kinds of ochre at least. The temperature difference found smaller for the zone with both pigments might be due to the poor absorption of the pigments compared to that of the lime within the 20-200 µm range. There also must be some effects due to the difference in diffusivity.

Finally, almost the whole edge patterns are visible. Only the two last lines at the bottom are not well marked. The detection length threshold is thus relatively low for our configuration as it is possible to detect a 4 mm painting line.

Figure 6: Photographs of the painting sample before (a) and after (b) covering it with a lime layer; processed black and white image (c) of the infrared visualization for a temperature drop by an inverse step flux.
Analysis and discussion of the transient thermal effects

The analysis of the contrast evolution helps understanding the pure conduction process when the source is obstructed. In particular, the conduction phase duration can bring some information on the material thickness. In Figure 7 can be seen the contrast at different times of the temperature decrease. For the studied case, the best contrast is obtained a few seconds after the end of the pulse. When analyzing the contrast for further times, the signal pattern seems less clear because of the noise of the ambient radiations.

In order to better understand the transient heat transfer phenomena, the 1D Fourier’s law analysis can be considered. Its resolution for a periodic thermal wave propagating through a semi-infinite homogeneous material leads to the assessment of the thermal diffusion length $\mu$ expressed as follows:

$$\mu = \sqrt{\frac{\alpha}{\pi f}}$$

where $\alpha = k / \rho c_p$ is the thermal diffusivity of the covering material and $f$ is the excitation frequency. The value of $t_{\text{start}} - t_{\text{end}}$ corresponds to the time delay before the apparition of the painted pattern at the surface of the sample. This time can be related to an excitation period equal to $\frac{1}{f}$. Considering the contrast through the time, the pattern appears more and more clearly. That is because the diffusion length (or the probe depth into lime) increases with the time. It can be noted that not all patterns appear at the same time, highlighting the fact that the lime layer thickness is not uniform. As most of the pattern is revealed after one second, the mean thickness of the lime layer can be estimated to 0.4 mm according to the equation (3).

![Contrast field $C_t^i$ (Arbitrary Unit) at $t = t_{\text{start}} + 0.01s$](image1)

Contrast field $C_t^i$ (Arbitrary Unit) at $t = t_{\text{start}} + 0.2s$

Contrast field $C_t^i$ (Arbitrary Unit) at $t = t_{\text{start}} + 1s$

Contrast field $C_t^i$ (Arbitrary Unit) at $t = t_{\text{start}} + 4s$

Figure 7: Paintings pattern revealed using the contrast expression given in equation (2) at several moments (0.01s, 0.2s, 1s, 4s) of the infrared acquisition
5. CONCLUSIONS AND PROSPECTS

The paper proposes a method based on the transient heat diffusion inside a lime layer and a painting layer. An extended range radiation wavelength source and a high resolution, mid-infrared camera at 1.5 - 5 µm working wavelength have been used. Both the technique principle and the analysis of the non-stationary phenomena that help improving the contrast were presented. Finally, reconstituted images of mural samples covered by a lime layer were shown. Not only the global painting pattern was revealed, but the contour of the interface between two pigments was also discovered. Since the lime is often used to hide murals, this method represents a major interest for both curators of historical monuments and other actors of the heritage.

This paper describes two thermal phenomena which influence the surface temperature and reveal the painting pattern: pure conductive for completely absorbed radiations at the lime surface, and radiative-conductive due to semi-transparence of the lime. In future work, the actual importance of both impacts on the will also be identified to best adapt the excitation source. Though results are satisfying, the method could be improved, for instance to reconstitute thinner paintings or covered by a thicker lime layer. The contrast might also be enhanced. A periodic excitation source could be used to reduce the noise-to-signal ratio. The study should then focus on the frequency response analysis, the development of a demodulation algorithm and the source filtering in order to suppress the radiation reflected on the sample.

REFERENCES