International Journal of Thermal Sciences 112 (2017) 188–198

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Spatial resolution optimization of a cooling-down thermal imaging method to reveal hidden academic frescoes

Tanguy Davin*, Bruno Serio, Géraldine Guida, Vincent Pina

Laboratoire Energétique Mécanique Electromagnétisme (LEME), EA 4416, Université Paris Ouest Nanterre La Défense, 50 rue de Sèvres, 92410 Ville d'Avray, France

ARTICLE INFO

Article history:
Received 3 December 2015
Received in revised form
4 October 2016
Accepted 11 October 2016

Keywords:
Infrared imaging
Cooling-down thermography
Thermal contrast optimization
Painting thermo-physical properties
Cultural heritage diagnostics
Defect analyses

ABSTRACT

A safe cooling-down infrared thermography technique was considered to reveal paintings covered by a limewash layer for cultural heritage investigations. The transient infrared image sequence permits to reconstitute the subsurface pattern by processing the thermal contrast. Given the interest in detection methods, we propose a theoretical optimization study of the spatial resolution of the method. This analysis, achieved with thermal simulations, is based on both the thermal sensibility and a specific formal spatial resolution criterion. Considering a bar pattern painting covered by a 0.5 mm thick limewash, we have shown a thermal sensibility up to 1.5 K. This value is about 75 times bigger than the thermal noise threshold of the used camera. The proposed spatial resolution criterion allows to establish optimal temporal settings giving the sharpest thermal contrast image. An academic hidden painting sample was especially made to validate this theoretical approach. Results show the suitability of the method to perfectly reveal hidden patterns and confirm the spatial resolution estimations predicted using the proposed theoretical model. Simulated and experimental thermal contrast profiles are in good agreement.

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 historical reasons such as political or religious events. These kinds of layer are generally made of lime or plaster diluted in water.

Optical techniques are powerful and versatile tools for the diagnosis of works of art. Numerous studies have considered techniques for restoration issues, once the paintings are discovered. For this purpose, some authors have focused on the pigments identification using various spectral methods [1–3]. Others studies have considered the material structure inspection of the paintings highlighting defects [4–7], earlier paintings restorations, underdrawings or *pentimenti* [8,9], and even controversial signatures [10]. Actually, there are numerous methods applicable for the detection of the presence of a work of art such as frescoes or mosaics.

The physical principles of methods for detecting objects buried in a wall made of lime or plaster depend of the used radiation. For instance, THz reflectometry can reveal wall structural discontinuities for the analysis of depths of interest (up to a few millimeters) [11,12]. Some particular materials such as graphite, metallic or dielectric patterns covered by a layer of pigments or plaster have been revealed using THz reflectometry and presented in Ref. [2]. Paintings hidden under a gesso layer was also recovered with the same method [13]. The use of terahertz radiations seems promising and is being developed in the last two decades but the pixels inspection number is still limited (object scanned point by point) so the acquisition requires a scanner and might be long. Furthermore, the THz sources needed to illuminate the scene are cumbersome, dear and limited in power. Therefore, the overall cost of this technology is still high.

Infrared methods are usually used in non-destructive testing of materials for inspecting or identifying defects using an either passive or active approach [14,15]. Passive thermal imaging methods are based on the fact that the features of interest are at a

* Corresponding author.
E-mail addresses: tanguy.davin@gmail.com (T. Davin), bserio@u-paris10.fr (B. Serio), gguida@u-paris10.fr (G. Guida), vpina@u-paris10.fr (V. Pina).

http://dx.doi.org/10.1016/j.ijthermalsci.2016.10.007
1290-0729/

higher or lower temperature than the background. They have been used for a long time to analyze paintings in order to find sketches or previous drawings since they are easily implemented and totally safe [16]. However, investigating on plaster-like walls is more delicate by using passive infrared thermography since in steady state, the thermal gradient at the surface of the studied object is low. A paint layer covered by a layer made of plaster or lime for instance might be hard to be detected using a passive method.

Active infrared thermal imaging methods are also often used to inspect materials as a non-destructive approach [17]. Most of these methods are applied to reveal defects inside material structures [18–20]. The classical active thermography method used to probe this kind of layers consists in exciting the surface using high power photographic flashes or halogen lamps for heating. The thermal excitation is either a pulse/step (depending on its duration) or a periodic heating. The response of the thermally excited surface is recorded using a thermographic camera. For a heat pulse/step, the temperature rise or decay or both are then analyzed while for a periodic source, the amplitude and phase of the surface temperature are demodulated using a specific algorithm (lock-in or pulsed phase thermography).

In this paper a cooling-down infrared imaging method is carried out for the detection of a painting and its contour. Only a few similar studies were conducted, to discover plastered mosaics [21,22]. In particular, some tesserae pieces covered by a 1 mm lime mortar layer were discovered, using a pulse thermography method improved by processing image algorithm [21]. The detection for consequently thicker covering layers (up to 3.5 cm) was also demonstrated [22]. The coupling of measurements with an inverse method also permitted to identify some features as mosaic thickness, location or thermal properties. The covering layer considered for the present study, about 0.5 mm thick, is relatively thin compared to those hiding mosaics, but our goal is to reveal the hidden pattern. Also, the painting layer is highly thinner than the mosaics pieces.

The proposed experimental method is based on the processing of an infrared frame sequence acquired using a high sensitive pre-triggered MWIR FPA camera at high speed rate during the cooling-down occurring after application of a heat flux stimulation. The thermal diffusion inside the plastered fresco was computed after an analysis of the thermo-physical properties.

The thermal surface contrast, referenced to the end of the thermal stimulation, is defined to highlight the subsurface objects. The thermal contrast difference is defined as the criterion representing the thermal sensibility of the method. It is compared to the camera NETD to check the possibility of detection. As expressed in Ref. [23], the aptitude to reveal subsurface defects by pulsed thermography must be optimized by considering the time dependence of the thermal system response. In this study, we have investigated the evolution of the thermal contrast for the proposed cooling-down method. This analysis, showing the thermal sensibility of the method, is important but results have revealed that the thermal diffusion that deteriorates the spatial resolution has to be considered as well. Therefore, a second criterion has been proposed to assess the influence of the processing time on the quality of the painting revelation by the thermal contrast function. This second criterion is defined by computing the surface temperature gradient relative to the maximum value. The combination of these two criteria highlights the choice of an optimum time value to process the infrared sequence giving the best thermal contrast image. This theoretical approach could be used to characterize the spatial resolution of all active thermography methods for defects detection. A bar pattern painting sample covered by limewash was realized to experimentally validate the method capabilities, in terms of presence detection and spatial resolution.

2. Method principle and thermo-physical characterization

2.1. Method principle

When the surface of the region of interest is heated using an external heat source, thermal waves flow inside the sample by thermal diffusion. Since the diffusion rate is affected by the existence of non-uniform thermal properties, the surface temperature over embedded paint layers will differ from the reference surrounding area.

However, the spectral nature of the source should be taken into account to understand the thermal excitation process in some cases. Indeed, the surface radiations are reflected, absorbed and possibly transmitted to deeper layers. Reflected radiations are added to the surface thermal emission and acts as a constant background that reduces the dynamic of the thermal imager. In this case, the absorbed part represents the required thermal surface excitation. The resulting heat flux propagated by thermal diffusion inside a wall depends on the absorption coefficient value of the limewash/plaster which is about 0.9 in the infrared band of a blackbody source at 500 °C for which the wavelength of maximum emission is 3.75 μm [12,24].

The transmitted radiations part could be used to generate a direct interface excitation as it was described in a previous work [25]. The spectral transmission of limewash and various pigments layers were previously measured. Since those materials are semi-transparent in far-infrared, their specific spectral signatures could be used to distinguish them from each other [26]. Considering spectroscopy measurements published in the previous reference, we estimate that only 0.01% of the total flux emitted by the used blackbody will be transmitted through the limewash layer. Consequently, the internal bulk absorption through the limewash was neglected in the current study and only an absorbed surface heat flux was taken into account for simulations presented in Section 3. Fig. 1 shows the principle of the radiative-conductive flux conversion used to thermally stimulate the buried painting layers.

We have chosen a black body source at 500 °C to excite the surface of the academic sample under test. In this configuration, the corresponding thermal flux absorbed at the sample surface is reasonably low, about 650 W/m^2. This mid-infrared thermal emission should not affect the integrity of the valuable sample and the source does not generate intense visible light such as halogen lamp sources commonly forbidden in historical places. Furthermore, in order to accurately detect the surface temperature singularities, we have used a high resolution and high-speed infrared camera combined with a specific image processing to improve the signal-to-noise ratio, in particular by averaging images as a boxcar filter.

The used mid-IR camera detects the radiosity of the limewash surface. This flux is composed of the surface emission (represented in thick green in Fig. 1) and the environment radiations reflection, mostly emitted from the black body during excitation. 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. A large aperture mechanical shutter was used to stop the heating excitation. The camera was pre-triggered to record the sequence starting before the shutter was closed. The signal processing was done from the recorded sequence of infrared images selecting the transient cooling-down.

2.2. Thermo-physical properties of mural paintings

In order to simulate the heat transfer inside a wall containing a hidden painting, the materials thermo-physical properties (thermal