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Active thermography testing and data analysis for the state of conservation of panel paintings

Yuan Yao[a], Stefano Sfarra[b,c,*], Susana Lagüela[d,e], Clemente Ibarra-Castanedo[f], Jin-Yi Wu[a], Xavier P.V. Maldague[f], Dario Ambrosini[b]

[a] Department of Chemical Engineering, National Tsing Hua University, Hsinchu 30013, Taiwan, ROC
[b] Department of Industrial and Information Engineering and Economics, University of L'Aquila, Piazzale E. Pontieri no. 1, Monteluco di Roio, L'Aquila, AQ I-67100, Italy
[c] INFN CHNet, Laboratori Nazionali del Gran Sasso, Via G. Acitelli 22, I-67100, Assergi, L'Aquila AQ, Italy
[d] Department of Cartographic and Terrain Engineering, Polytechnic School of Avila, University of Salamanca, Hornos Caleros, 50, 05003 Avila, Spain
[e] Applied Geotechnologies Research Group, University of Vigo, Rúa Maxwell s/n, Campus Lagoas-Marcosende, 36310 Vigo, Spain
[f] Department of Electrical and Computer Engineering, Laval University, 1065, av. de la Médecine, G1V 0A6 Quebec City, QC, Canada

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ABSTRACT

The restoration of Cultural Heritage wouldn't be possible without the financial resources to meet Cultural Heritage needs. A smart procedure to reduce in time and funds spent for restoration is linked to a planning of the diagnostic interventions acting to predict incipient defects undetectable to the naked eye. One of the main methods to fulfil this task is infrared thermography (IRT). The aim of this study is to examine the efficiency of various mathematical techniques in thermographic data processing, with respect to the thermal excitation procedure and the type of artificial defect in a panel painting sample. One of the thermographic analyses performed was based on the pixelwise algorithm for time-derivative of temperature (PATDT). With this algorithm, Newton's cooling law was applied pixel per pixel, resulting in the computation of the cooling rate of each pixel. In addition, the capabilities of the multivariate statistical analysis methods, independent component thermography (ICT) and sparse principal component thermography (SPCT) were also investigated. In the present case study, the authors inspected possible pathologies resembling splitting areas (*i.e.*, detachments) in real panel paintings, with the consequent change in the heat transfer coefficient and the heat capacity. The feasibility of the different analysis methods was illustrated with the application results.

1. Introduction

Looking into the Scopus database putting *non-destructive* and *panel painting* as keywords in the search engine, it is possible to notice how the first optical tests applied to this type of objects were used at the end of the seventies/beginning of the eighties. A series of benchmarks were published in those years [1–3]. However, the use of solid-state detectors [4], accelerator gadgets [5], micro-Raman and X-ray fluorescence spectroscopy [6], fibre-optic Raman spectroscopy [7], shearography and terahertz imaging [8], reflectography and infrared thermography (IRT) [9], parametric loudspeaker [10], molecular spectroscopy and unilateral NMR [11], synchrotron-based X-ray laminography [12], digital speckle pattern interferometry [13], ultrasound phase-shift analysis [14], structured light system technique [15], and helium-Raman system [16], was subsequently (or contextually) developed and applied by the diagnosticians with the aim of inspecting each part, material or element constituting a panel painting.

In particular, infrared methods operating at infrared wavelengths (3–14 [μm]) can provide information on the subsurface features and the thermal properties of the painting, including thermal conduction [17–19]. Flash thermography was used to study these thermal properties because it requires low heat exposure, acquires data with relatively high signal-to-noise ratio (SNR), and may identify subsurface features which cannot be revealed by other NDT techniques commonly used in the conservation studio, such as X-radiography, 1–3 μm infrared reflectography, and ultraviolet (UV) radiation [20].

An IRT inspection allows to explore the multi-layer structure of a panel painting up to the support. Although the support is a valuable aspect of the history and the physicality of an object, the worth of a panel painting is placed on its painted surface. The durability of the support leads to the long-term preservation of the paint, therefore conservators work on the support to conserve the decorated surface.

* Corresponding author. Department of Industrial and Information Engineering and Economics, University of L'Aquila, Piazzale E. Pontieri no. 1, Monteluco di Roio, L'Aquila, AQ I-67100, Italy.
E-mail address: stefano.sfarra@univaq.it (S. Sfarra).

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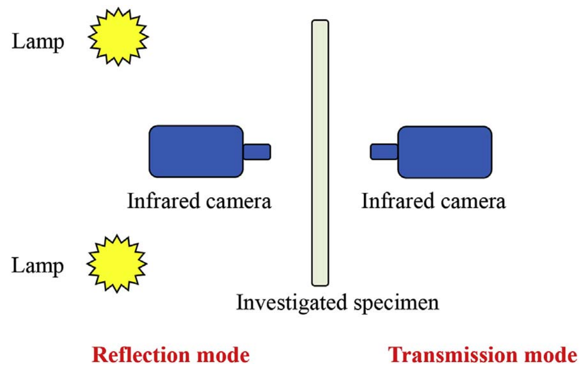

Fig. 1. Illustration of reflection and transmission modes.

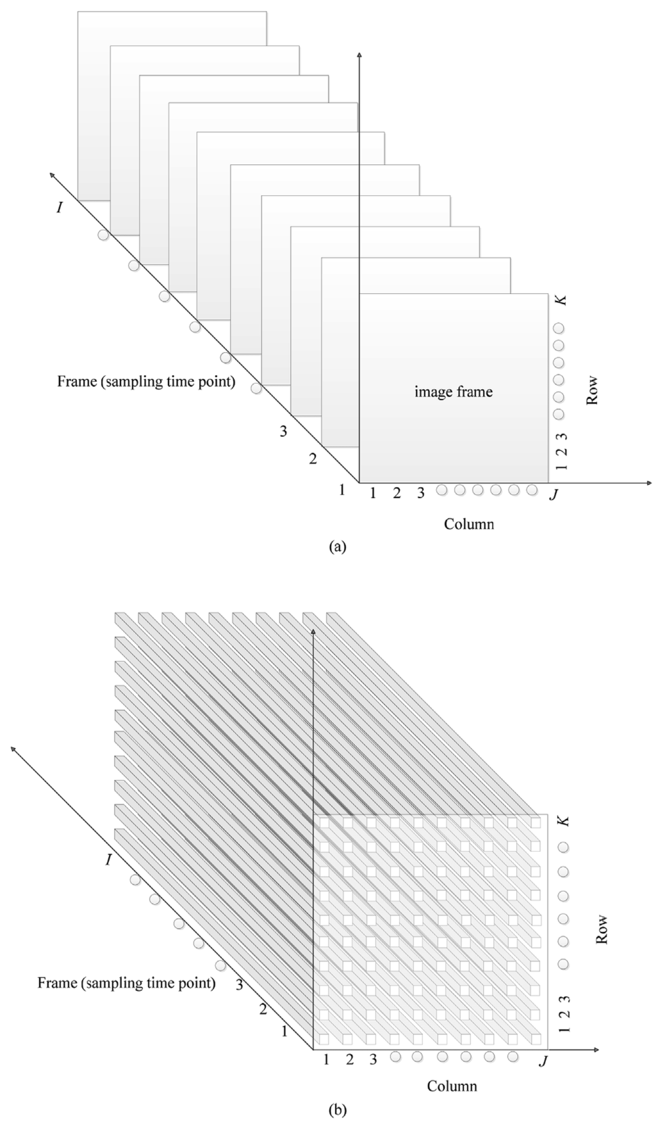

Fig. 2. Structure of a thermographic dataset. (a) A time sequence of thermograms. (b) A 2-D hyper-image.

Whilst damage to the wood structure of a panel painting may be caused by its conservation and acquisition history, a variety of other factors such as the quality of the wood selected, biological infestations and inappropriate housing in bad environmental conditions also play a part in the deterioration of the wooden structures. Damaged timbers and climatic fluctuations induce constant expansion and contraction movements within the support leading to distortions, detachments and cracks of the upper layers [21,22]. The attention of the present manuscript is focused on the latter damages. To fulfil this purpose, a panel painting (named: *The Madonna*) manufactured following the rules of the art master *Cennino Cennini* (1370–1427) and containing fabricated defects was used.

Specifically, innovative algorithms, including pixelwise algorithm for time-derivative of temperature (PATDT), independent component thermography (ICT) and sparse principal component thermography (SPCT), are applied to the thermographic data to reveal the positions of the defects. The rest of this paper is organized as follows. In section 2, the essentials of active thermography are introduced, followed by the PATDT, ICT and SPCT algorithms described in section 3. Section 4 presents the results of the experiments together with the thermographic data analysis using the different methods. Finally, section 5 ends the paper with conclusions.

2. Active thermography testing for subsurface defect detection

Infrared thermography is a popular NDT technique, which uses an infrared camera to capture the surface temperature of the target specimen. By using thermography, thermograms are acquired in time sequence, showing changes in the temperature distribution.

Taking into account the way of thermal process activation, thermography is usually classified into two categories: passive thermography and active thermography. In passive thermography, the investigated object, such as a biological organism, is naturally at different temperatures from the background. In active thermography, on the other hand, an external energy source is required for artificial thermal excitation. Given the possibility of controlling the intensity of the external energy source, the artificial thermal excitation can reach deeper atoms in the object, and therefore information can be obtained from more internal layers. Thus, for defect detection in panel paintings, active thermography should be adopted because there is no inner heat source inside the test specimens and interest lies both on its surface and its internal layers.

The experimental procedure of active thermography usually consists of two stages. In the heating stage, the external energy source is applied to heat the investigated object. After that, the heating power is turned off so that the object cools down gradually. This stage is called cooling stage. Because of heat diffusion, the surface temperature response is time-dependent in both stages.

According to the relative position between object, heat source and infrared camera, active thermography has two different working modes, i.e. reflection and transmission, as illustrated in Fig. 1. In reflection mode, the heating is applied on the same side of the object as the thermographic acquisition device, i.e. the camera. Hence, in the heating stage, the camera mainly measures the reflected radiation from the object surface. This is what the name of "reflection mode" refers to. On the contrary, in transmission mode, the heat source and the infrared camera are set up on different sides of the test object. In this situation, the measured radiation is that transmitted through the object.

The thermographic dataset can be perceived as a three-dimensional (3-D) matrix with a size of $I \times J \times K$, which contains a series of thermograms. As shown in Fig. 2 [23], I is the number of frames acquired by the camera, and J and K are the total numbers of pixel rows and columns in a thermogram, respectively. Each frame is collected at a certain time point. From another point of view, this dataset can be represented as a hyper-image whose resolution is $J \times K$. In this hyper-image, each pixel contains a one-dimensional (1-D) data vector recording the temperature profile at a certain location.

When active thermography is applied for subsurface defect detection, the temperature profiles in intact and defective regions show different patterns, because of the discontinuity in the inner structures of the material. Therefore, it is possible to identify the defects according to the temperature contrasts. In order to enhance the performance of defect detection, thermographic data analysis methods are often a necessity.