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The use of pulse-compression thermography for detecting defects in paintings

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ABSTRACT

Interest in the conservation of paintings grows year by year. Their periodic inspection is essential for their conservation over the time. Thermographic non-destructive inspection is one technique useful for paintings, but it is essential to be able to detect buried defects while minimising the level of thermal stimulus. This paper describes a pulse-compression infrared thermography technique whereby defect detection is optimized while minimising the rise in temperature. To accomplish this task, LED lamps driven by a coded waveform based on a linear frequency modulated chirp signal have been used on paintings on both a wooden panel and a canvas layer. These specimens contained artificially fabricated defects. Although the physical condition of each painting was different, the experimental results show that the proposed signal processing procedure is able to detect defects using a low temperature contrast.

1. Introduction

Active Thermography (AT) is a Non-Destructive Evaluation (NDE) technique widely used in different fields of research and industrials applications, as in material characterization [1], food inspection [2] and in cultural heritage diagnostic [3]. AT always relies on exciting the sample with a heating stimulus to achieve the required thermal contrast, though many different measurement schemes and post-processing algorithms can be employed [4]. For cultural heritage objects, AT is commonly implemented using Pulsed Thermography (PT), where the sample *e.g.* a bookbinding [5], bronze statue [6] or painting [7] is excited by an impulse from a flash-lamp. Additional thermal stimuli that have been reported include hot air [8], cold air [9], quartz lamps linear systems [10], heating plates [11], halogen lamps [12] and laser heating [13]. Information about defects and other structural changes are retrieved by analysing both the heating and cooling response as a function of time and location.

Although PT is relatively simple to use, care should be taken when applying a pulsed stimulus to cultural objects such as paintings. This is because abrupt variations of the sample temperature could create thermal shocks and hence damage to the sample, although these can be anticipated using numerical simulations centred on heat transfer phenomena [14,15]. In particular, colour changes (known as thermochromism) may result, where a particular pigment may react to long (or repetitive) exposures to high temperatures, leading to degradation of the perceived colour. In addition, an exposed area may drift to another shade of colour. Certain colours formed by pigments are more susceptible to this drift [16]. For example, in vivianite ($Fe_3(PO_4)_2{\cdot}8H_2O$, blue), heat-related damage can be observed at temperatures as low as 70 °C, causing colour changes in both pure vivianite [17] and oil paint layers containing it [18]. Thus, minimising the temperature variation is of primary importance. The use of low-power excitation is therefore desirable in such cases, but this leads to a significant reduction of the Signal to Noise Ratio (SNR) that could affect the effectiveness of the PT analysis.

Fortunately, techniques have been developed capable of improving the SNR of AT measurements in case of low-power sources. One approach

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is Lock-in Thermography (LT), where the heating stimulus is modulated at a specific frequency [19]. The acquired thermograms are then processed in the frequency domain, thus obtaining phase and magnitude images of the investigated item at that frequency [20]. LT is widely adopted as it provides a significant gain of SNR. However, the depth of penetration is set by the modulation frequency, and the amount of information retrieved is lower than that from PT, which excites a greater measurement bandwidth [21]. Therefore, efforts have been made to combine the advantages of both schemes, leading for example to Pulse Phase Thermography [22], and the more complex Multi-Frequency Lock-in Thermography [23].

Another possible approach is to exploit the positive features of pulse-compression techniques [24]. The application of coded excitation signals and pulse-compression for studying thermal phenomena was pioneered by several rearch groups led by Mandelis [25–27] and Mulaveesala [28–30]. Subsequently, various PuCT procedures have been proposed [31–33]. In fact, the Pulse Compression (PuC) algorithm outputs an accurate impulse response estimate that is very similar to that obtainable from PT, even when low-power sources are used. The modulated heating stimulus is in the form of a coded excitation, where the bandwidth B and the duration T of the signal are uncorrelated. Hence, the frequency content of the coded signal can be tailored to suit the investigation of a given sample, while T can be increased almost arbitrarily to achieve the desired SNR [34–37]. These properties can be usefully applied to inspect paintings, using low-power heating sources to keep surface temperatures relatively low. Moreover, the use of coded excitations and PuC allows both frequency and time domain analyses to be performed. A frequency domain analysis can be carried out directly on the raw acquired data; the time domain analysis can be executed after the application of the PuC algorithm. It is worth noting that the use of pseudo-random modulated heating stimulus has been used in infrared thermography [25], and recently applied in AT for cultural heritage diagnostic by Candoré et al. [38]. However, here the thermal impulse response was estimated using an Auto Regressive Moving Average algorithm (ARMA) to model the process. In PuCT, the thermal impulse response is estimated by applying a deterministic procedure based on application of a matched filter. In addition, in Ref. [38] the thermal source consisted of halogen lamps driven by a pseudo-random code while in the present paper the heating stimulus is realized with LEDs driven by a chirp signal.

Here we extend the above by investigating the use of PuCT for the NDE of paintings. PuCT has been performed on two different specimens, representing two painting types: one being a painted wooden panel [39,40], the other a painting on canvas [41,42], both containing artificial defects. It should be noted that each of these samples aims to mimic the painting technique of a specific artistic period. In particular, the panel painting was constructed following the Cennino Cennini's rules [43], thus mimicking a painting technique often used during the XV century. The painting on canvas is close to contemporary art where acrylic-based paint is used [44]. Therefore, the artistic period to which they refer is completely different. For the current setup, the heating source consisted of eight LED chips which provided an overall power of 110 W, low enough to avoid overheating of the sample. The coded waveform used for this work was chosen carefully so as to minimise damage to the paintings. It was a linear frequency-modulated chirp signal, a sinusoidal signal whose frequency varies linearly as time elapses [45,46], where the instantaneous chirp amplitude varies smoothly with time. Thus, the combined use of PuC and a well-designed linear chirp was able to damp any thermal shock to the paintings (especially when compared to PT), while minimising increases in the sample temperature.

2. Description of the samples

2.1. Painting on canvas

Here, a linen canvas was used as support, and after a preliminary treatment (sizing), the canvas was fixed onto a wooden frame. An outline

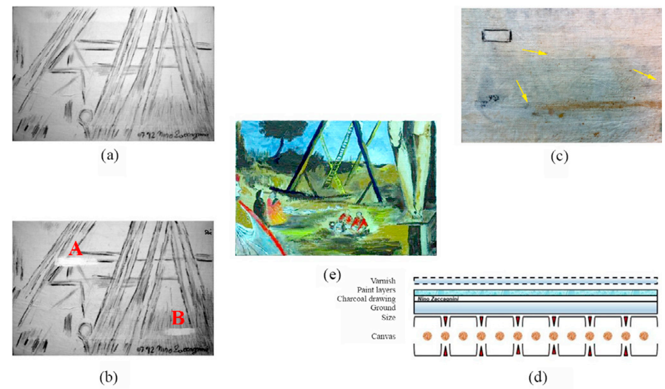

Fig. 1. Painting on canvas: (a) the preparatory drawing, (b) defects A, B, (c) back view with embroideries, (d) the layers constituting the sample, and (e) front view of the final sample.

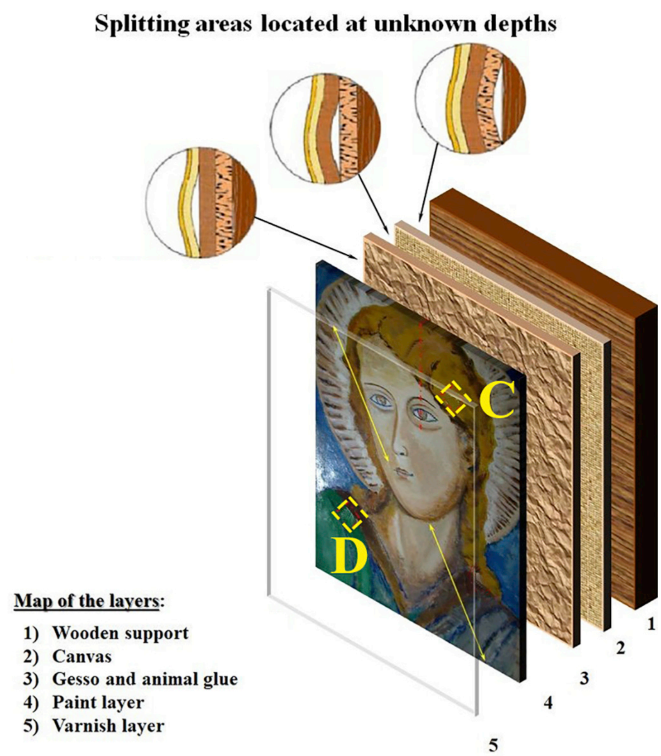

Fig. 2. Panel painting: on-plane position of the fabricated defects and sequence of the layers.

charcoal crayon sketch was drawn on the canvas (Fig. 1(a)). Two Mylar defects were then placed between the size and the ground layers, see Fig. 1(b) and (d). Defect A (4.5 × 1 cm) consisted of two superimposed Mylar layers, and defect B (4 × 1 cm) was formed from one layer. Acrylic paint and varnish layers were then applied over the defects and the canvas was both embroidered (see the arrows in Fig. 1(c)), and other repairs simulated using a crochet-hook. The final appearance of the painting is shown in Fig. 1(e).

2.2. Wooden panel painting

The panel painting, based on a poplar wood substrate with dimensions (20 × 25 × 2 cm), is shown in Fig. 2(a) along with the positions of the defects (labelled C-D). Poplar was frequently used for the fabrication of panel paintings in the Italian schools [43]. Splitting areas were simulated by inserting a thin sponge covered with Mylar (defect C) and a