Infrared Physics & Technology 77 (2016) 325–334

Contents lists available at ScienceDirect

Infrared Physics & Technology

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

Regular article

Wavelet subspace decomposition of thermal infrared images for defect detection in artworks

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HIGHLIGHTS

- Pseudo-random binary excitation based infrared imaging for fault detection.
- Automated fault identification using thermal images.
- Wavelet basis selection criterion.
- Mutual information based decomposition level selection.
- Contrast enhancement metric for quantitative analysis of fault detection algorithm.

ARTICLE INFO

Article history:
Received 25 December 2015
Available online 17 June 2016

Keywords:
Non-destructive testing
Subspace decomposition
Wavelet transform
Fault detection
Mutual information
Infrared thermography
PRBS excitation

ABSTRACT

Health of ancient artworks must be routinely monitored for their adequate preservation. Faults in these artworks may develop over time and must be identified as precisely as possible. The classical acoustic testing techniques, being invasive, risk causing permanent damage during periodic inspections. Infrared thermometry offers a promising solution to map faults in artworks. It involves heating the artwork and recording its thermal response using infrared camera. A novel strategy based on pseudo-random binary excitation principle is used in this work to suppress the risks associated with prolonged heating. The objective of this work is to develop an automatic scheme for detecting faults in the captured images. An efficient scheme based on wavelet based subspace decomposition is developed which favors identification of, the otherwise invisible, weaker faults. Two major problems addressed in this work are the selection of the optimal wavelet basis and the subspace level selection. A novel criterion based on regional mutual information is proposed for the latter. The approach is successfully tested on a laboratory based sample as well as real artworks. A new contrast enhancement metric is developed to demonstrate the quantitative efficiency of the algorithm. The algorithm is successfully deployed for both laboratory based and real artworks.

1. Introduction

The detection and identification of faults in different materials has been a major research avenue for numerous industrial applications. Diverse techniques like Gamma and X-rays, Ultrasounds, Foucault currents, and Nuclear Magnetic Resonance are conventionally utilized for non-destructive testing of materials [1–7]. Recently, techniques focusing on thermal radiations, such as photo-reflectance, photo-acoustics, mirage effect and photo thermal radiometry, have been tested on the laboratory scale for non-invasive testing of materials [8–11]. Photo-thermal radiometry is one such technique which requires a relatively simple experimental setup [12]. The test material is excited by an external heat source, changing the local thermal conditions of the material. The thermal response of the material to this excitation is then captured by a thermal infrared camera. This thermal response depends on various material properties such as thermal conductivity, diffusivity, emissivity, specific heat and characteristics of the excitation sequence. These properties are in turn governed by factors such as material structure (including fissures

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http://dx.doi.org/10.1016/j.infrared.2016.06.018
1350-4495/

and holes), physicochemical processes taking place in the material, delamination and sedimentation.

Degradation of ancient artworks is a natural process, however, adequate preservation can significantly enhance their durability. Faults developing in the artwork are efficient indicators of its deterioration and a precise mapping of these faults may aid in timely remedial actions. The detection of these faults is challenging, requiring adequate precaution not to cause permanent damage to the material of the artwork. This work focuses on *frescos* which are a special type of layered mural structures. Due to the environmental effects, delamination might occur at the interface of the layers. This is the working definition of a defect in the artwork that will be used throughout the current paper. The conventional method used for exciting the material is the pulse excitation method which consists of heating the material over a relatively long time and then allowing it to cool down [13]. It is relatively easier to identify the faults in the pulse excited thermal images. However, the prolonged heating involved in the process, risks overheating and thus damaging the material.

An alternate approach is to use pseudo-random binary sequence (PRBS) based excitation. For pulse excitation method, the step heating results in a greater transfer of thermal energy to the material under analysis as compared to the PRBS excitation. In photo-thermal radiometry, the faults are identifiable by their significantly different contrast. Even though, PRBS excitation is more favorable from material health conservation perspective, it necessitates more intensive post-processing to retrieve useful information about the defects. An efficient detection algorithm should be able to reveal localization map of defects in the material, even if these defects are not visible in the raw data. Some signal processing based methods were previously developed by the authors for detecting defects in artworks using PRBS excitation [14]. The initial findings revealed some interesting results regarding defects in the material. However, the interpretation of the final results could not be established.

The aim of this work was to develop a novel processing scheme for detecting defects in artworks. We propose an algorithm based on the wavelet decomposition of thermal infrared responses to PRBS excitations. The algorithm exploits the multi-resolution capability of wavelet transform and approximates a subspace, efficiently isolating the defect information from other influences. It allows suppressing the effects of pictorial layer, measurement noise, potential interference patterns due to multiple excitation sources and nonhomogeneous heating of the tested material. The method is applied spatially to extract the useful subspaces which are further temporally processed to attain a unified representation of the defects. As there is no universal criterion for the selection of wavelet basis function, we also propose a scheme for basis selection. Moreover, the paper also contributes an automated mechanism for determining the wavelet decomposition level. Even though the main focus of the paper is proposition of a defect detection algorithm, it is pointed out that the final detection parameter is a potential indicator of the fault dimension (depth and diameter). The proposed method is validated on a sample test material containing defects of various depths and diameters. This allows optimization of the algorithm parameters. The algorithm is then applied on a real artwork without any a priori knowledge of the fault locations. The results are very promising for detecting even weaker faults both in qualitative and quantitative terms.

The paper is organized to start with an overview of acquisition setup and state-of-the-art methods. This is followed by the experimental materials and the proposed formulation of the problem. The results of the proposed approach on the acquired datasets are discussed in the subsequent section. The paper is finally concluded to summarize the contributions of this work.

2. State-of-the-art methods

This section describes the experimental setup for photo-radiometry system including the excitation and acquisition setup. It then discusses the state-of-the-art approach in analyzing the acquired thermal data to develop the motivation for current research.

2.1. Excitation and acquisition system

The experimental setup for photo-thermometry is illustrated in Fig. 1(a). The artwork is heated simultaneously by two halogen lamps, each one with a power of 500 W. The lamps are symmetrically placed around the infrared camera, approximately 50 cm from the artwork. The temporal excitation pattern of these two lamps is simultaneously controlled by a pseudo random binary sequence (PRBS). The smallest duration of each binary pulse in this sequence represents the excitation time (T_e). Different excitation times are considered in this work to study their influence on the detection of faults. The excitation times used in this study, $T_e = 0.5$ s, $T_e = 1$ s, $T_e = 2$ s and $T_e = 5$ s result in $N_t = 2048$, $N_t = 1024$, $N_t = 512$ and $N_t = 256$ pulses, respectively. An illustrative excitation pattern is shown in Fig. 1(b). The absorption of the incident heat flow depends on the thermal properties of the material. The surface defects like cracks effect the optical characteristics of the material. Such defects have the most dominant signature in the thermal image and are instantly visible. The sub-surface defects are less pronounced and appear after some time as the heat diffuses through the material. Such defects are air pockets in otherwise uniform material, resulting in non-uniform heat diffusion and back-scattering from the surface. These phenomena are exploited in this work for defect detection. The back-scattering radiation are captured by a A20 FLIR thermal Infrared (IR) camera. This bolometer camera, working in long wavelength range (7.5–13 μm) with a thermal sensitivity of 0.12 °C at 30 °C, was placed around 50 cm from the sample. The image acquisition of the IR camera is synchronized with the excitation lamps, latter being configured as a slave. One thermal image is obtained per pulse of the input PRBS sequence, resulting in a total of N_t images. Even with sustained efforts to select ideal placement of light sources and camera, practically, the problem of non-uniform heating cannot be ruled out. The raw data cube, $\mathcal{Y}$, exist in the Hilbert space $\Re^{N_x \times N_y \times N_t}$, where N_x and N_y correspond to the dimension of the test material in pixels and N_t corresponds to the total number of acquisitions.

2.2. State-of-the-art: subspace decomposition of thermal responses

Hilbert spaces, equipped with the notion of inner product and continuity, provide a formal way of defining subspace decomposition, the approach adopted in this work. The raw data are a superposition of multiple sources including defects, background pictorial layer, in-homogeneous heating and measurement noise. The Hilbert space containing the raw data can be decomposed into its subspaces, each representing single or multiple aforementioned sources. Subspace decomposition based matrix filtering techniques have been used in diverse applications [15–19]. Singular Value Decomposition (SVD) and Wavelet decomposition are common methods of subspace decomposition. In this paper, SVD based technique, previously developed by the authors for defect identification [14], is compared with the new technique developed in this work. In SVD based subspace decomposition, it is hypothesized that temporal evolution of thermal responses of the defects and background are different. The raw data cube, $\mathcal{Y} \in \Re^{N_x \times N_x \times N_t}$ is