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Multipurpose, dual-mode imaging in the 3–5 μm range (MWIR) for artwork diagnostics: A systematic approach

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ABSTRACT

We present a multi-purpose, dual-mode imaging method in the Mid-Wavelength Infrared (MWIR) range (from 3 μm to 5 μm) for a more efficient nondestructive analysis of artworks. Using a setup based on a MWIR thermal camera and multiple radiation sources, two radiometric image datasets are acquired in different acquisition modalities, the image in quasi-reflectance mode (TQR) and the thermal sequence in emission mode. Here, the advantages are: the complementarity of the information; the use of the quasi-reflectance map for calculating the emissivity map; the use of TQR map for a referentiation to the visible of the thermographic images. The concept of the method is presented, the practical feasibility is demonstrated through a custom imaging setup, the potentiality for the nondestructive analysis is shown on a notable application to cultural heritage. The method has been used as experimental tool in support of the restoration of the mural painting "Monocromo" by Leonardo da Vinci. Feedback from the operators and a comparison with some conventional diagnostic techniques is also given to underline the novelty and potentiality of the method.

1. Introduction

Optical methods are excellent tools in metrology and diagnostics [1,2]. The main features of these techniques, namely the non-contact approach, the flexibility and the full-field measurement, make them very well suited to artwork diagnostics. In particular, the full-field measurement was a key factor for their success and "imaging methods" are becoming more and more important, thanks to the rapid development of acquisition devices and image-processing algorithms and hardware. This impressive development led to the introduction and optimization of optical diagnostic techniques, both qualitative and quantitative [3–11], and to the wide diffusion of imaging investigative tools in the multidisciplinary field of cultural heritage, on which image-related sciences have a great impact [12,13].

Infrared (IR) imaging is widely used in nondestructive analysis of paintings as it allows a non-contact and wide-field inspection in situ of their multi-layered features, namely the painting support, the pictorial layers, and the surface layers. Notable techniques are IR reflectography, which exploits the low scattering of the IR wavelengths up to 2.5 μm across the pictorial layers for imaging the features below the surface [14,15] (e.g. preparatory drawings and repaintings), and IR thermography in the Long-Wavelength Infrared (LWIR) range (from 8 μm to 12μm), which exploits the thermal contrast at the object surface induced by heat waves propagation for retrieving information about the deep structures [16,17] (e.g. internal defects and/or lack of homogeneity). Given the complexity of artwork's materials and stratigraphy, a comprehensive diagnostics usually requires a multi-technique approach; thus, for example, thermography can be coupled to holography [18] or to reflectography [19] and imaging in different IR bands proved useful [20]. Specific imaging methods can be tailored to extract information from the different matter-radiation interaction properties of the layers. The thermal quasi-reflectography (TQR) approach [21] takes full advantage of the surface-interacting capability of the Mid-Wavelength Infrared (MWIR) wavelengths (from 3 μm to 5 μm) for imaging the pictorial layer in frescoes, where conventional IR reflectography is not effective, allowing the detection of features that are not imaged with traditional methods.

In this work a procedure, based on TQR, is proposed for IR diagnostics exploiting dual-mode acquisition in the MWIR range.

The paper is organized as follows: in Section 2 a schematic description of the proposed diagnostic procedure is given. Section 3 is devoted to the illustration of the basic features of TQR integrated in a dual-mode setup. In Section 4 the proposed procedure is treated in detail. In Section 5 the effectiveness of the procedure for the non-destructive

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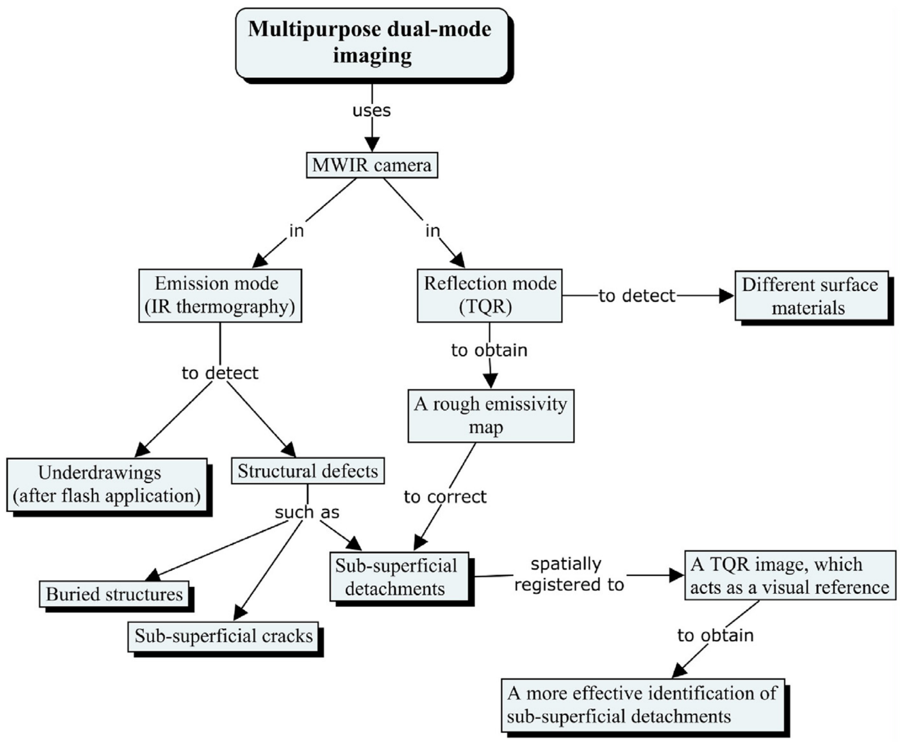

Fig. 1. Schematic description of multipurpose dual-mode imaging.

analysis of mural paintings is shown in an exemplar case study: the notable restoration of the mural by Leonardo da Vinci of "Sala delle Asse" in the Sforza Castle in Milan, Italy [22]. Feedback from cultural heritage operators and comparisons with traditional diagnostic tools are also given to underline the novelty of the method.

2. Multipurpose, dual-mode MWIR imaging in a nutshell

The main concepts of the proposed dual-mode procedure are summarized in Fig. 1. Using a setup based on a thermal camera and multiple radiation sources, two radiometric image datasets are acquired: the image in quasi-reflectography modality and the thermal sequence in emission modality. The dual-mode thermal stack is integrated to gain information.

The detection of structural defects by IR thermography is well described in literature [16]. Regarding the possibility to discover underdrawings, IR thermography after flash application [17] is not ideal: because of the low resolution of IR cameras, a dedicated equipment results in a better choice [15,19]. However, as all the measurements described in Fig. 1 are taken by the same recording device, images are spatially aligned and image fusion could be easily accomplished. In the following, the focus is on a full exploitation of TQR potentialities and on the detection of sub-superficial detachments by IR thermography powered by TQR results.

3. The TQR imaging technique integrated in a dual-mode setup

The core of the TQR imaging modality is the observation that an object with constant emissivity at room temperature has a very low emission in the MWIR band; if the surface temperature is 293 K, it emits about 1% of its thermal energy in the 3 µm to 5 µm range, as follows by the in-band Plank radiant exitance. Therefore, by sending MWIR radiation, properly matched with the thermal camera, and limiting any heating of the surface object, the acquired signal is dominated by the reflected radiation. As shown in [21], TQR imaging has the key feature to reveal details not detectable by conventional techniques.

Fig. 2. Dual-mode imaging setup.

In Fig. 2, a sketch of the dual-mode acquisition setup is given. A single thermal camera (geometry and optical configuration are fixed) is used for recording dataset both in emission mode and in reflection mode. The system employs multiple excitation sources. The heating sources, used for the thermal stimulus in emission mode measurements, are two quartz tungsten halogen lamps (1250 W). To prevent the transient cool down effect of the sources, a shutter has been applied after their switch off. In the present setup, the shuttering is mandatory; in fact, the residual heat of the high temperature halogen bulb matches the spectral response of the MWIR sensor. This is of particular importance when inspecting painted surfaces that are not high in emissivity: indeed, the transient lamp cool down signal, reflected back, could dominate or affect the recorded signal in thermal inspection [23].

The non-heating sources, used for reflection mode measurements, are custom designed as detailed in the following section.

3.1. TQR sources

The ideal TQR source should:

- exhibit a large, stable and smooth spectrum in the MWIR range;