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The challenge of infrared imaging of frescos: Thermal Quasi-Reflectography unveils hidden features of artworks

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1. Infrared diagnostics of multi-layered paintings

Infrared imaging is widely used in heritage diagnostics allowing the noninvasive analysis of extended painted surfaces. Wide-field techniques and selective use of proper infrared bands enable the mapping of many features both at surface and subsurface levels, according to the specific radiation interaction properties of the artwork materials. In particular, near-infrared reflectography, by exploiting the capability of the near-infrared spectrum (0.8-2.5 μm) to penetrate the different pictorial layers, is able to reveal hidden features such as preparatory drawings, pentimenti (changes in the artwork made by the artist himself), or subsequent repaintings [Aa.Vv., 2005]. It is well known that for the study of canvas and panel paintings, such technique is one of the most powerful tools in the hands of art historians and restorers [Van Asperen de Boer, 1968]. The more recent spectral techniques have further boosted near-infrared imagery both of ancient and contemporary paintings [Delaney et al., 2010; Daffara et al., 2011]. Acquisition of images in multiple bands improves the observation of the different painting features, which can be detected in optimal spectral windows according to the optical transparency of painting matter in the infrared range.
From this point of view, the analysis of mural paintings is a difficult challenge. Traditional reflectography is less effective when a fresco layer is present, due to the different optical properties of the pictorial layers (different scattering medium).
As recently shown [Ambrosini et al., 2010], the integration of reflectography and thermography represents an interesting approach in artwork diagnostics. These two techniques, which work in the different spectral ranges of near and far-infrared (7-14 μm), provided, jointly used, significant information about the conservation status of panel paintings. On one hand, near-infrared inspections allows going through the making of the artwork and its restoration steps; on the other hand, thermography allows different properties of materials, in addition to superficial and structural defects, to be outlined. Logical developments of this integration were the adding of the mid-infrared band (3-5 μm) and the extension to different artworks, e.g. frescos.
We have recently demonstrated a novel tool for infrared imaging of artworks, named Thermal Quasi-Reflectography (TQR) [Daffara et al., 2012], able to unlock in mural paintings details that are not revealed by the conventional techniques. The underpinning idea is to extract information from the mid-infrared energy reflected by the object, which results to be strongly related to the

properties of surface materials.
Thermal bands are conventionally being used in non-destructive testing in relation to the emissive behavior of the target object, and widely applied to mural paintings for the inspection of structural defects (inner support or paint delamination) [Ibarra-Castanedo et al., 2008]. Here the concept of classic thermography, where the radiation emitted by the surface is recorded and then correlated to the temperature distribution (the thermogram) is taken on reverse. Effectively, it is a quasi-reflectography in the thermal wavelengths, in which the emitted radiation is minimized in order to properly record the reflected quote. The result is the mid-infrared reflectogram, which allows the discrimination of many features in the pictorial layers, related both to the artwork materials and technique and to the fresco surface decay.
In this brief paper we trace the key-points of the new TQR technique: 1) basic principles and instrumentation to enable operative measurements; 2) main diagnostic results. Examples of the image results obtained on fresco models are shown, while applications on original artworks can be found in [Daffara et al., 2012].

2. Thermal Quasi-Reflectography (TQR)

2.1. Basic principles

In infrared imaging we can distinguish between reflective and thermal bands. Near-infrared imaging up to 2.5 μm in wavelength forms images using reflected light, e.g. the infrared radiation backscattered by the painted surface. Conversely, the mid-infrared and the far-infrared regions are thermal bands. Imaging in these wavelengths records the infrared radiation emitted from the target and then displays this radiation as a temperature map on the target surface.
The key point of the TQR method is to use a thermal camera to form images from the radiation reflected by the object; obviously, the obtained images are not related to temperature distribution on the object surface. It is shown that at room temperature, the emissive contribute in the mid-infrared range is negligible (about 1%) with respect to the corresponding reflective quote, therefore, a reflectography can be performed in this spectral range by means of a radiometric camera and a proper artificial source matched in the 3-5 μm band, under the condition of limiting the heating of the surface.
The set up for measurements (sketched in figure 1) is simple: image acquisition is performed in reflection geometry, in broadband and wide-field mode. Anyway, thermal cameras working in the mid-infrared range (mainly based on cooled MCT or InSb array sensors), are still very expensive compared to near and far-infrared (bolometric) devices. A suitable source provides uniform irradiation over a “large” area, (e.g. field of view of 1 sqmt) for field measurements. Infrared lamps controlled in power with the spectrum matched to the mid-infrared quasi-reflection range can be obtained starting from quartz elements (carbon, tungsten or alloy filament) and a suitable filtering infrared window (e.g. sapphire); halogens are peaked in the near-infrared, but also provide a quote of mid-infrared.

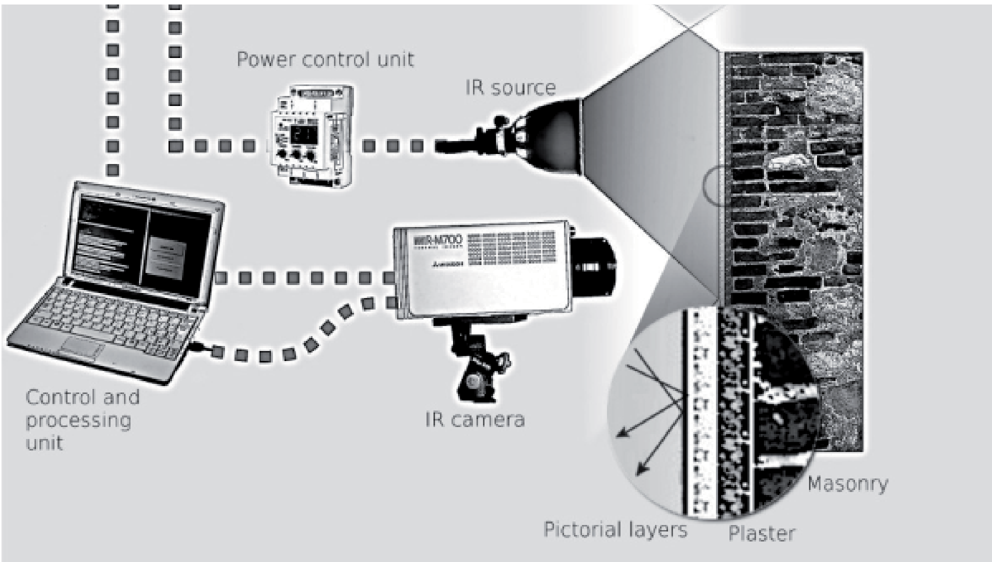

Fig.1 - Measurement setup for TQR: mid-infrared camera, infrared source controlled in power, real-time image acquisition and processing. The detail outlines the layered structure of fresco: pictorial layers, plaster, and support

2.2. Diagnostic results on frescoes

A painting on wall, or fresco, can be described as a layered structure (see figure 1). The wall support is primed with plaster layers, which serve as a base for the painting; in a traditional fresco, the pigment is dissolved in water and then applied on the wet plaster leading then to the unique carbonated layer. Traditional reflectography, based on near-infrared, is not very effective on mural paintings, although some information could be retrieved as, in many cases, frescos have integration and retouches in "secco" technique (separate paint layers with binder). The TQR technique, based on mid-infrared, has a big potential in the diagnostics of such complex artworks, as discussed below.
The figure 2 compares mid-infrared imaging in reflection mode, i.e. TQR, and in emission mode (active thermography), showing that TQR imaging is strongly related to superficial features, while thermography detects subsurface defects (blue arrow).
The TQR technique has been experimented on both target samples and real artworks thanks to the collaboration with the Opificio delle Pietre Dure (OPD), Florence.
The figure 3 shows the application of TQR to a fresco model (a copy from old masters constructed in 1930, based on traditional material and technique) and

Fig.2 - Mid-infrared diagnostics of lime plaster sample: reflection mode TQR (left) and emission mode thermography (right). The blu arrow indicates a subsurface defect detected in the emission image and not in the reflectogram. A void volume on the opposite side of the sample creates the subsurface discontinuity while the main surface is layered with Vinavil

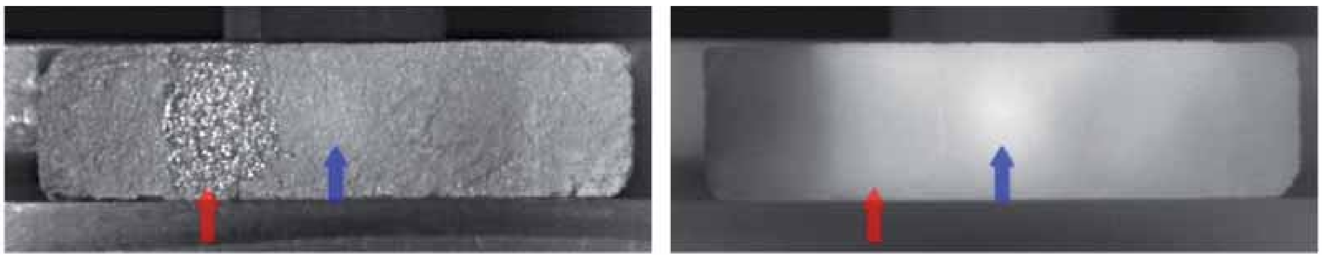

Figure 3. Analysis of a fresco model (OPD laboratories). From the left: VIS image, near-infrared reflectography (1µm Si CCD), TQR image (3-5µm), far-infrared thermography (thermogram after heating pulse). The detail: mid-infrared TQR (left), near-infrared scanner reflectography (2.2 µm)

the comparison with the traditional techniques reflectography and thermography. Mid-infrared maps the red pigment cinnabar (mouth), which is highly reflective, and some features of the surface layers (skin, hat, and background) that are not detected in the near-infrared. As expected, far-infrared thermography provides a clear detection of the deep texture of the support together with an inner void defect at plaster level (near the shoulder). The detail in figure 3 compares the mid-infrared image and the reflectogram acquired with multispectral scanner at long near-infrared wavelenghts (2.2 µm) and shows the complementary information related to different penetration and reflectance response in the two bands. TQR in the mid-infrared detects the material response in the more superficial fresco layer (background area) and drawing traces (face contour), near-infrared detects the response in deeper painting layer and maps underneath drawing traces.

TQR information is related to the materials in the surface layer. Differences in the reflectance response allow the discrimination of some materials such as high reflective pigments. Mid-infrared spectrum carries back information related to the absorption bands of pictorial matter. The low reflectance is probably due to the absorption features of the organics materials, however an interpretation based exclusively on the absorption bands could be misleading. The mid-infrared reflectance is determined by factors related to the material composition, to the density and microstructure, and to the surface roughness.

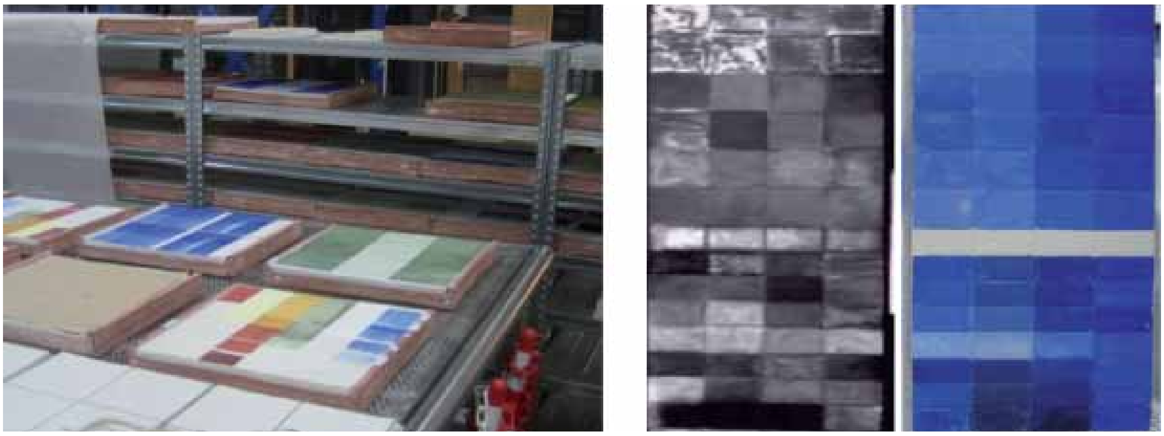

Fig.4 -TQR applied to fresco samples (OPD laboratories). Different kind of lapis lazuli pigments (columns) layered with different fresco techniques (rows). Reflectance in the mid-infrared varies with the combinations of pigment-binder, the technique, and the surface roughness

As such, TQR has the potential to detect the presence of different materials and binders, and to discriminate the response of different surface layers.
Pictorial materials created, layered, and finished with different techniques exhibit different reflectance responses. A systematic study of the mid-infrared reflectance is being carried out on a set of controlled samples of different materials (pigments and binders) and execution techniques, constructed at the Wall Painting Laboratory of the OPD (figure 4).
The TQR technique is effective in the study of surface decay. As example of this application, a laboratory study on controlled samples is shown (figure 5), where the technique is applied to map the sulphated areas in the fresco surface. A brush was used to apply a 2% solution of Sulphuric acid in a sample of lime plaster. Neither in the visible spectrum nor in the near-infrared the area where the solution has been applied is observable, but in the 3-5 μm region the area attacked with the acid solution exhibits higher reflectance. This behavior is due to the different physical and chemical aspects of the material surface involved. The gypsum created after the sulphatation probably has a lower absorbance compared with lime plaster, but some reflectance increment could be related to the different morphology of the sulphated surface.
On real artworks, the TQR technique was effective for the selective mapping of painting materials, e.g. high reflective pigments as cinnabar or green earth glauconite, finishing touches, subtle traces in bianco di San Giovanni, and a clear detection of different-aged organic painting integrations. Different execution techniques, e.g. fresco or tempera, also exhibit different behaviors. Application of the TQR to the masterpiece “Resurrezione” by Piero della Francesca, Museo Civico of Sansepolcro, can be found in the [Daffara et al., 2012].

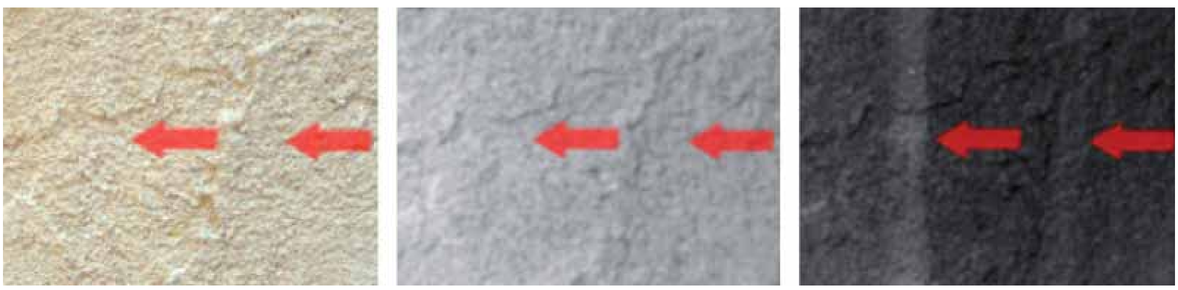

Fig.5 - TQR diagnostics applied to a sample of lime plaster attacked by sulphate decay. From the left: VIS image, near-infrared reflectography (PtSi 1.2-2.5 μm), TQR (3-5 μm). Red arrows indicate the sulphated areas, which are detected only by TQR technique

3. Conclusion

Thermal Quasi-Reflectography is a new diagnostic technique, which is demonstrated to have a great potential in the diagnostics of frescoes. The results obtained strongly encourage further developments and applications on field. Based on the recording of mid-infrared radiation reflected from the surface, TQR is well suited to the differentiation of surface materials. It can provide pigments differentiation and identification of repainting and retouching. TQR can be used as a first screening for a more effective sampling with point techniques, e.g. spectroscopy in the mid-infrared range. Following the approach of imagery integration, TQR can be integrated with the other imaging techniques for a multi-layer representation of the artwork and a more comprehensive diagnostic documentation.

An interdisciplinary effort, involving conservators and scientists, is needed. Thanks to the collaboration with the Opificio delle Pietre Dure, the TQR method is being tested both on controlled samples and fresco models as well as on important artworks. While conservators should test TQR on real artworks in situ, scientists should optimize the performance in laboratory: from the optical acquisition chain (crucial is the mid-infrared source), to the reflectance data interpretation (crucial is the correlation of TQR with spectroscopy in the 3-5 μm) in order to stretch the imaging technique towards materials mapping.

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