Infrared vision for the nondestructive assessment of panel paintings

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Abstract
Artificial infrared (IR) vision can be used for the nondestructive assessment of panel paintings in three different but complementary wavelength bands of the infrared spectrum: near IR reflectography can be exploited for the detection of underdrawings whilst mid and long IR can be used for the detection and characterization of internal defects.

FEATURE ARTICLE

Introduction

Infrared (IR) vision can be defined as the capability of biological or artificial systems to detect infrared radiation. A wide variety of commercial infrared cameras are available nowadays providing the possibility to exploit these capabilities at different IR wavelengths. The IR spectrum is located at wavelengths longer than the visible (VIS) spectrum and can be subdivided using different definitions according to the field of application. Figure 1 proposes one of such classifications taking into account the atmosphere high transmission windows and the type of detectors being used. In the case of panel painting inspection, three IR spectral bands are of interest: (1) the near infrared band (NIR) between 0.75 and 2.5 µm, (2) the mid wave infrared (MWIR) between 3 and 5 µm, and (3) the long wave infrared (LWIR) between 7 and 14 µm.

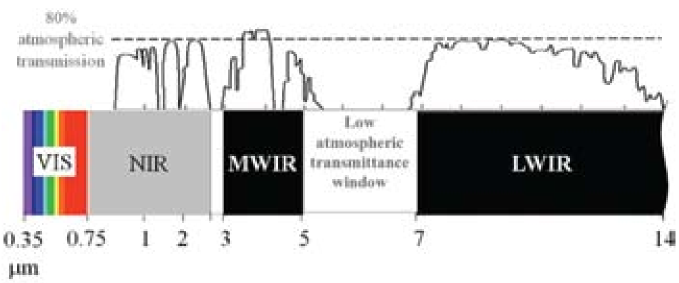

Figure 1: Visible (VIS) and infrared (IR) spectrum bands subdivided according to the three high-transmissivity atmosphere windows (80% transmissivity determined trough a 18 km horizontal path at sea level and 17 mm of precipitated water): near (NIR), mid wavelength (MWIR) and long wavelength (LWIR) infrared.

There exist some fundamental differences between the NIR and MWIR/LWIR bands being somehow complementary for the nondestructive testing and evaluation (NDT&E) of artworks. In one hand, NIR *reflectography* is employed for the assessment of ancient paintings providing information underneath the painting layers. IR *thermography* on the other hand, exploits the principle of heat diffusion gradients on dissimilar materials for the detection and, in some cases, the characterization of subsurface anomalies.

The aim of this paper is to describe the NIR reflectography and IR thermography techniques for the NDT&E of artworks. Experimental results on a panel painting are presented in order to discuss the potentials and limitations of both techniques.

Near infrared reflectography

When exposing a painting to a broad-band light source (from ultraviolet to the far IR) as illustrated in Figure 2, part of the radiation will be absorbed by, another fraction of the radiation will be transmitted through and the rest will be reflected from the incident surface, depending on the radiation wavelength. For instance, a visible camera will capture the light (in the visible spectrum 0.35 to 0.75 µm) reflected from the painting surface, providing information about colors and textures.

Keywords: *near infrared reflectography, infrared thermography, artworks inspection, underdrawings, paintings, defect detection and characterization*

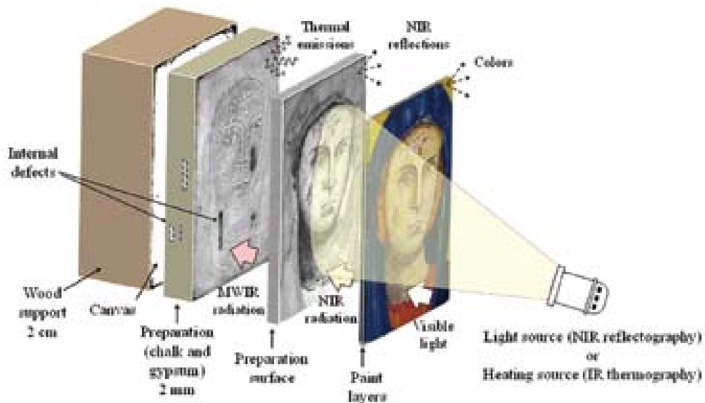

Figure 2: Typical structure of panel paintings and behaviour of the different radiation types from a light source for NIR reflectography and a heat source for IR thermography.

The NIR part of the radiation, which contains practically no thermal emissions, can penetrate thin layers of painting before being reflected back to the surface from an non-absorbing media such as the preparation surface (usually made of chalk and gypsum) and will eventually be absorbed by carbon based (or other absorbing) elements, if present. Most of the oil paints used for panel painting (usually linseed oil with inorganic suspended oxide or mineral salt pigments [1]) are transparent to NIR light, whilst carbon derivatives (graphite and charcoal) are opaque in this spectral region.

The transparency in the NIR band is a complex function of the optical characteristics of (1) the pigment color (with brown and gray being in general more transparent than some light colors, whilst black is most opaque [1]), (2) the underdrawing material, (3) the paint layer thickness (typically a fraction of millimeters [2]), and (4) the detector wavelength (transparency increases between 1.0 and 2.5 μm for different configurations [3], generally showing a peak near to 2 μm [4]). A NIR camera can be used to reconstruct two-dimensional (2D) images, i.e. *reflectograms*, of the reflected light under the painting layers. Interesting applications include the detection of guiding sketches and signatures (opaque to NIR radiation) drawn by the artist prior to the application of painting layers; the detection of hidden paintings (painters often use a previously painted canvas or change their mind during the painting progression), the monitoring of the restoration processes required on aging cultural heritage artworks, and the detection of intentional and unintentional alterations.

NIR reflectography has been studied since the 1930s. At the beginning, photographic films were used. Although NIR photography works are interesting, restrictions on the spectral band (0.7 to 0.9 μm) and time delays (due to film development) limited the wide spread of the technique (an interesting NIR photography investigation can be found in [5]). It wasn't until the 1960s, after the work of Van Asperen de Boer [6], that the use of Vidicon cameras (0.9 to 2.0 μm) first and digital cameras (1.1 to 5 μm) later, began to be used routinely by many recognized art Museums [7], [8], [9]. The next generation of NIR reflectography systems is the multi-spectral (up to 14 spectral bands) single-point scanners, which considerably diminish the effects of optical and geometrical non-uniformities with respect to multi-detectors arrays [2], [10]. These systems however, are slow, heavy and too complex to be commercialized at the moment (year 2010). The use of commercial NIR cameras and the required accessories (lenses, filters, and light sources) is still the preferred alternative for artwork inspection given its easiness compared to single-point scanners.

Infrared thermography

When a painting is exposed to a heat source (optical or other), the IR radiation is re-emitted back from this object at wavelengths longer than the NIR, i.e. MWIR and LWIR, which is mostly the result of thermal emission. There is less reflected light in this case since most of the energy is absorbed by the different painting components and emitted back to the surface. The IR part of the incident light in the MWIR and LWIR bands is transformed into heat and it propagates through the painting by conduction (see Figure 2). An IR camera will be able to see the thermal emissions from the internal parts of the painting at the surface. This is a well-known technique referred as *infrared thermography* [11] that has been progressively adopted in many areas for the NDT&E of materials [12], [13]. Contrary to NIR reflectography, IR thermography provides three-dimensional (3D) matrices typically composed of several hundreds of thermal maps, *i.e. thermograms*, each one representing a given time before, during and/or after heating.

There are basically two experimental configurations: pulsed thermography (PT) and lock-in (or modulated) thermography (LT). PT, which uses a short heat stimulation, is very attractive for the NDT&E of artworks given its easiness of deployment, its rapidity, the fact that large surfaces can be inspected at once, and the possibility of providing quantitative results (subsurface defect characterization: size, depth, thermal properties). Nevertheless, signal and image processing techniques must be used in order to improve the signal-to-noise ratio (SNR), enhance defect contrast, correct for artefacts (thermal, geometrical and optical non-uniformities), and characterize the defects. In addition, heat should be delivered in a controlled manner to avoid damaging the artwork. In LT, the specimen is continually stimulated using a modulated heat source. In this case, the amplitude and the phase delay (or simply the *phase*) of the thermal response are of interest. Phase images or *phasegrams* are particularly interesting since most of the detrimental thermal and optical effects observed in PT are considerably reduced. Furthermore, LT users have a better control of the amount of energy delivered to the inspected piece and better contrast can be achieved since a large number of images are averaged through processing to obtain the final result. Nevertheless, since the maximum detectable depth is inversely related to the modulation frequency, several experiments are needed in order to inspect different depths. In consequence, data acquisition duration is in general much longer than in PT, especially if low modulation frequencies are used. Besides, Fourier transform analysis can be used to retrieve the phase information from a PT experiment, in a similar manner that is done by LT but with the advantage of obtaining a large number of phasegrams, representing different frequencies, with a single experiment. This technique is called pulsed phase thermography (PPT) [14].

Comparative results

In this study, NIR reflectography and pulsed phase thermography are examined for the NDT&E inspection of a panel painting. The inspected specimen, called *The Madonna* (shown in Figure 3a), contains some underdrawings and 4 fabricated internal defects made of biaxially-oriented polyethylene terephthalate (boPET) film located at different locations (shown in Figure 3d) and depths.

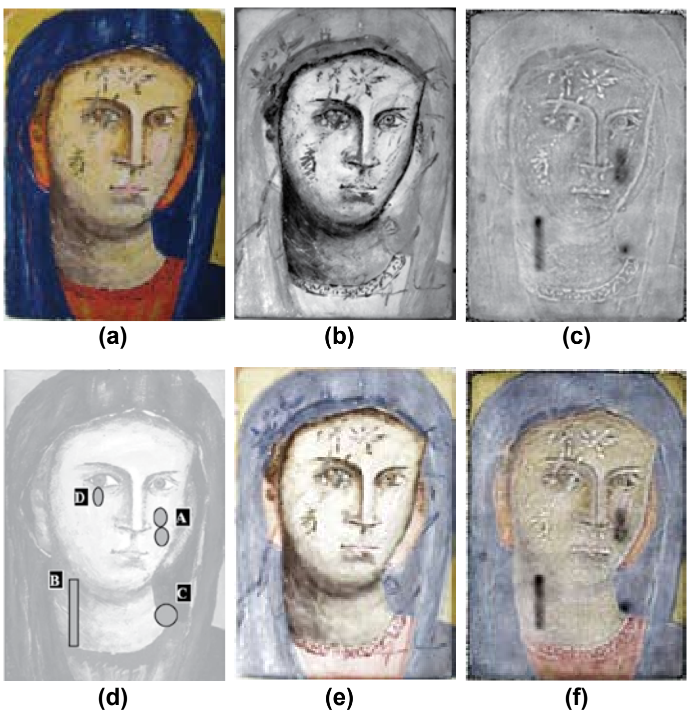

Figure 3:* The Madonna *specimen: (a) photograph of the specimen, (b) NIR reflectogram (0.9-1.7 µm), (c) phasegram (f= 0.09 Hz) obtained by pulsed phase thermography, (d) photograph with the approximate location and shape of the fabricated defects, (e) visible + NIR reflectogram combined image, and (f) visible + PPT phasegram combined image.

Although the exact depth of these artificial defects is unknown (original data from the manufacturer is unfortunately missing), a previous work on this specimen provides some rough estimations using pulsed thermography [15]. Data from this reference is summarized in Table 1.

Defect	Dimensions reported in [15]	Depth range as reported in [15]
A	D=5 mm, each	0.3 - 0.8 mm
B	37 x 7 mm	0.8 - 0.9 mm
C	D=8 mm	> 1.4 mm
D	-	> 2.0 mm
Painting	210 x 150 mm	

***Table 1: Dimensions and depths of the artificial inserts in* The Madonna.**

Figure 3a shows a photograph of *The Madonna* where some surface scratches, resulting from bad handling over the years, can be identified. A reflectogram obtained with a NIR camera working in the 0.9 to 1.7 µm band is presented in Figure 3b. As can be seen, several underdrawings appear in this image: a maple leaf, the inscription "CE" (inverted), a bird and a small square can be observed on the upper left side of the painting. Some other sketches around the right eye, the artist signature in the bottom left and some guiding sketches (on the left and around the neck) can be seen as well. In contrast, there is no indication of the fabricated boPET inserts in the reflectogram since they are located under the surface preparation layer (not transparent to NIR radiation) as suggested in [15]. Another possibility is that, even in the case that one or more of the boPET inserts were located between the preparation surface and the painting layers, *i.e.* in the zone of transparency to the NIR radiation, they would not be detected because boPET films are also transparent to NIR radiation in the working band of the camera. As some studies have shown [16], PET parts almost completely transparent to NIR radiation from 1 to 1.6 µm, which covers the most part of the operation spectrum of the NIR camera used in this study (0.9 to 1.7 µm). In the referred work, transparency curves of PET components contains two peaks around 1.7 µm and 2 µm, which may indicate that further experimentation using NIR detectors working around one of these two peaks will help to gather additional information about the inserts depths.

The specimen was also inspected by PT using a MWIR camera (3 to 5 µm). A 3D thermogram matrix containing 1800 images was recorded and processed by PPT [14] to produce phasegrams. The phasegram presented in Figure 3c shows 3 of the 4 fabricated inserts reported in Figure 3d, *i.e.* defects A, B, and C. Only defect D is not detected, probably because it is too deep and/or too thin to produce enough thermal contrast with respect to the panel. Only one phasegram (*f*= 0.09 Hz), showing the best overall contrast for all the detected defects, is presented for simplicity. However, better contrast can be achieved for a particular defect at higher or lower frequencies, depending on their depth. Figure 3e and Figure 3d present two composition images showing the results from NIR reflectography (Figure 3b) and IR thermography (Figure 3c), respectively, superimposed to the visible photograph of *The Madonna* (Figure 3a). These two images provide a good indication of the location of both, underdrawings and subsurface defects.

In addition, there are two unexpected features that can be seen in the phasegram of Figure 3c and the composed image of Figure 3f. The first one is a small round defect at the left that can only be seen by thermography and not by NIR reflectography. Hence, it is possible that this defect corresponds to foreign material trapped in the preparation surface. It is also possible that this defect, detected by the IR camera, is located between the painting layers and the preparation but it is transparent in the operating NIR band. Figure 4a presents a raw thermogram highlighting this defect (left) and the thermal profiles (right) for a defective (dotted line) and a non-defective (plain line) areas (from the average of 3x3 pixels windows). It can be seen from the profiles that this defect starts to be visible a fraction of a second after heating (t=0.08 s), which indicates that it might be located inside the preparation surface.

The second feature is a small triangle that can be seen in the right eye of *The Madonna* (see Figure 3c and Figure 4b, left). The origin of this defect is even more unclear and intriguing. Its shape corresponds almost perfectly to the painting (white) used in the right eye sclera but its thermal signature in Figure 4b (right) corresponds to a less absorbing material (colder) that is visible immediately after heating. The white painting used to cover this area should have, in principle, absorbing properties similar to the other painting colors used for the production of the specimen. This is evidently not the case. Further analysis and testing will be required to gain more information.

Finally, although the present work is limited to panel painting inspection, it is possible that other cultural heritage objects and buildings, where is common to find multi-layer structures similar to panel painting, can be inspected, e.g. mosaics with gold or marble tesserae covered with different plasters.

Conclusions

From these results it can be concluded that the combined operation of NIR reflectography and IR thermography can be exploited for a more complete NDT&E assessment of the integrity of artworks. It should be mentioned however that, judging from the results presented here, the correct interpretation of results requires a good knowledge and experience on panel painting production to be able to arrive to pertinent conclusions. In one hand, NIR reflectography allows to retrieve the information about underdrawings, provided that the combination of optical properties of the painting layers and the underdrawing material, the paint layer thickness, the detector type, the source wavelength and the optical filters are all appropriate for the case in hand. This can help to study the artistic process during painting, artist intentions, and even help to attribute an artwork piece to its corresponding author in the case of unsigned or damaged paintings. On the other hand, thermography allows to detect internal defects in a nondestructive manner, which would be difficult to identify without using intrusive techniques. In this case, heating sources are needed to produce enough heat to detect internal defects. Finally, it is important to point out that special care should be taken to avoid damaging the artwork.

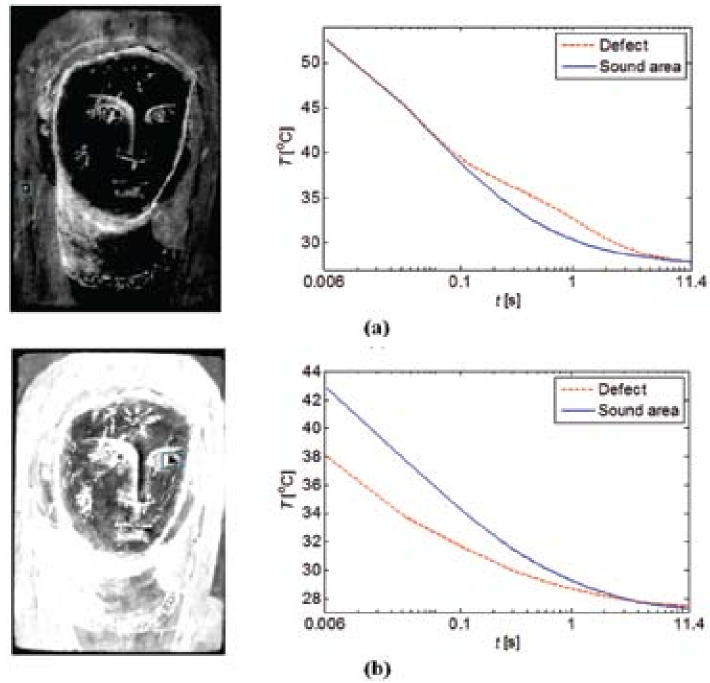

Figure 4: Raw thermograms of **The Madonna** *specimen at different times highlighting two interesting features: (a) a small round defect at t=0.2 s, possible foreign material trapped in the preparation surface, and (b) a triangular defect in the right eye at t=0.006 s, probably having optical/thermal properties dissimilar to the rest of the painting. The corresponding thermal profiles (3x3 pixels windows) of defective (dotted line) and not defective (plain line) areas are also shown at the right of each thermogram.*

Acknowledgements

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NDT Past

Korean Society for Nondestructive Testing

This photograph was taken on the occasion of the first meeting of the Korean Society for Nondestructive Testing held in Seoul and was sent to us by Mr. Len Baxter, former president of L. E. Baxter Ltd., Montreal and now with AECL. Mr. Baxter is shown seated second from the left in the photograph.

The Canadian Society for Nondestructive Testing extends congratulations and best wishes to this new Society for an active and successful future.

Editors Note: *This announcement about the creation of the Korean Society for Nondestructive Testing (KSNT) in March 1980 was published in the Aug / Sep 1980 issue of the CSNDT Journal. The KSNT was subsequently recognized as an incorporated body by the Korean Ministry of Science and Technology in June, 1981.*

In the ensuing 30+ years it has grown to over 1700 members, 124 student members, and 114 corporate members, and like the Canadian Institute for NDE, serves the purpose of facilitating academic research and promoting practical applications of the nondestructive testing techniques. More information about the KSNT and other national NDT societies is available from the CINDE website at http://www.cinde.ca/links.phtml?view=other

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