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A Comparison of Near- and Mid-Infrared band reflectography in the diagnostics of artwork

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Abstract

The work addresses the important role of conservation science in the pre-restoration diagnostics of paintings. The authors demonstrate how mid-infrared (3-5 µm band) methods, namely, Pulse thermography, Pulse Phase thermography and Principal Component thermography, can be used for the analysis of wood-based and canvas-based paintings, illustrating the power of this approach in the detection of delaminations, degraded regions, as well as uncovering scenes which have been painted over (pentimenti). The results of the application of thermographic methods are compared with the results achieved through Near-Infrared reflectography (0.7-1.1 µm band) which is recognized as one of most conventional methods for art diagnostics.

1. Introduction

One of the primary problems of preservation and conservation of cultural artifacts that art scientists face in their work is the task of collecting as much information on the object under treatment as possible. This information includes background study of the provenance and the artist, as well as data on the physical structure of the object. This includes the materials used, the locations of degraded regions, and the defects present. The latter is necessary for developing the strategy for further conservation measures and often requires a highly experienced and knowledgeable restorer. Some information about the artwork, such as the dimensions of the hidden defects and determination of how severe they are is very difficult to be ascertained, although this information is of the utmost importance since defects left without treatment could destroy the artwork in a very short period of time.

Starting in the last century scientific tools became more actively applied in the field of preservation and conservation of works of art. These tools can be separated into two categories: the first are methods devoted to the analysis of materials and the second group of tools are imaging methods utilized for analyzing the structure of a test sample. There is a retinue of methods available such as X-radiography, Terahertz radiography, and Ultrasonic imaging, to name a few. The method of particular interest is Near-Infrared reflectography (NIR), which acquires images in 0.7-1.1 µm, and has been in use for many decades. It's mainly helpful in locating *pentimenti* under different types of paint, which often provides some clues as to the identity of the artist and helps reveal forgeries by finding retouched regions and altered signatures. An innovative new tool known as thermography which operates at longer wavelengths and has been in use in industrial diagnostics for a long time recently became involved in the field of art diagnostics – primarily for defectoscopy of frescoes and panel paintings.

In this work the authors compare the capabilities of both NIR and thermographic imaging methods in terms of their powers to reveal defects present as well as to locate over-painted areas. Being encouraged by the success of advanced signal processing procedures in thermography – namely, pulse phase thermography (PPT) and principal component thermography (PCT), the authors also try to apply these approaches to artwork analysis.

2. Theory

2.1 Paintings and their analysis

A painting represents a multilayered structure. In many cases it consists of a *support* (wood, canvas, metal, etc.), a *ground layer*, forming the basis for the *paint layer(s)* on top of it and *varnish*, protecting the paint from the environment and providing additional stylistic effects [1, 2]. All these layers have different mechanical properties and inevitably degrade with time. A classic example of such degradation is the detachment of the layers caused by the drying of materials which have different contraction properties [3]. In this way a delamination may form and spread over a portion of the painting remaining undetected until the moment when the artwork is totally disintegrated. In order to prevent this, special diagnostic procedures are to be used for early detection of defect formation with subsequent preventive restoration measures.

2.2 Near Infrared and Mid-Infrared visualization

NIR essentially utilizes the radiation of electromagnetic spectrum just beyond the visible region – between 0.7 and 1.1 µm. Due to the lower attenuation, these waves penetrate deeper into materials than electromagnetic waves of the visible band, and can aid in deciphering the features hidden under opaque layers of material. It was demonstrated [4] that most paints used for art purposes become more transparent when observed in longer wavelengths. This fact is commonly known to art restorers and NIR is often used with the primary goal of locating pentimenti. The techniques, instruments and numerous schemes for this method are well described in literature [5, 6, 7, 8].

Thermography relies on the monitoring of surface temperature of the analyzed object, and the experiment usually requires the acquisition of a number of thermal images (snapshots). After these images are acquired they can be either analyzed directly or processed in order to improve the quality.

In cases where the sample itself is not heat-generating, an external heat impact is utilized. The heat flux propagating from the heated surface into the bulk of the sample causes a gradual change in the surface temperature which remains uniform in the absence of subsurface defects. If any defects or foreign materials are present, the surface temperature distribution may change accordingly. This method is known as Pulse Thermography (PT) and may be considered as an express analysis because of its simplicity and the short monitoring time [9]. Though simple and reliable, PT has some drawbacks such as the effect of non-uniform heating, affecting the image and making it harder to interpret.

There are several techniques directed to reduce such effects as well as to improve the sensitivity of the method itself. One of them, called Pulse Phase Thermography (PPT) describes the pulse applied to the sample as a superposition of harmonic signals of different frequencies [10]. The final images are constructed from the phase part of Fourier decomposition applied to the temperature-vs-time evolution of each pixel of the image. This approach was demonstrated to be less affected by the non-uniformity of heating applied [11]. At the same time, it allows for estimating the depth of the defects found provided that the thermal diffusivity of the material is known. In the case of artworks analysis, the information on the thermal properties of all the materials used is usually unknown. Instead, the method of PPT may be used for qualitative flaws determined by constructing the phase images using the lowest Fourier frequency which corresponds to the maximum penetration depth into the material. In the experiment mentioned below, the PPT images correspond to the lowest Fourier frequency in the decomposition.

Another method, principal component thermography (PCT), is based on decomposition of the same data as acquired for PT and PPT in the orthogonal statistical modes [12]. The data acquired in the experiment is used for the construction of a set of orthogonal vectors, each of which corresponds to one of variation modes of the data set. After this decomposition is performed, one can neglect one or several first vectors, thus removing the prevailing trends in the data and study the remaining information. In the majority of cases the remaining part helps reveal the defects limiting the effects of non-uniform heating, as well as suppressing some noise caused by the electronics of the thermal imager.

First, the 3D array of thermographic data acquired in PT experiment is converted into a 2D array by unwrapping each of the 2D thermal snapshots into one column of a new matrix (Fig.1a). In this way the data acquired is represented by a number of variables (points of the sample's surface) measured over some time period.

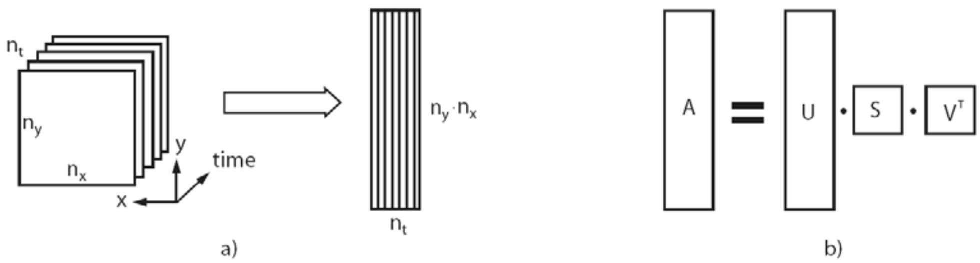

Fig.1. *a) Transforming 3D data array into a 2D matrix; b) A scheme of singular value decomposition.*

The simplest way to extract the set of orthogonal vectors necessary for PCT is performing singular value decomposition on the array of the data collected (Fig.1b):

$$A = U \cdot S \cdot V^T , \qquad (1)$$

where matrices U and V contain sets of mutually orthogonal vectors, and S is a diagonal matrix containing so called *singular values*, each value describes how much data in the initial data set can be described by this or another vector. Usually most of the variance of the data set decomposed is described by the first several vectors while others correspond to statistical noises and uncertainties. In order to resolve the subsurface features making little contribution to the observed thermograms, the main temperature trend (the first vectors) is to be removed, and the projection of the initial data onto the remaining vectors is to be analyzed.

For the experiments conducted in this work the following scheme was applied. After the decomposition, all the singular values in matrix S were set to zero except one or two values with orders higher than one. After that matrix A was reconstructed and the data were analyzed. If the defect was still invisible, the order of the singular values taken into account was increased and matrix A was analyzed again. The procedure was repeated several times until the image became distorted with statistical noises. In most of the cases retaining components #3 and #4 was enough to reveal the artifacts of interest.

3. Instrumentation and equipment

A Near-Infrared camera, Fujifilm S3 Pro UVIR in combination with Wratten 87 NIR-pass filter, was used for NIR experiments. The spectral sensitivity of the camera is up to 1.1 µm. The experiments were conducted using a reflection scheme and the paintings were illuminated with an incandescent light bulb.

For the purposes of thermal inspection, a mid-infrared thermal imager FLIR SC4000 was applied. The device has a spectral sensitivity in the range of 3-5 µm and an InSb detector, 256×320 in size. During each experiment a series of thermal snapshots was generated (with framerate up to 400 frames per second) and then processed with MATLAB.

In order to apply heat pulses to the surface of the tested samples, a flash system Speedotron 4803CX was utilized, which allowed for the production of a 1/175 s light pulse with a single 4.8 kW power flash lamp. The flash system was controlled via a relay system connected to a computer.

4. Samples and the results of analysis

The samples analyzed included:

- 6 patches of canvas with pentimenti drawn in lead pencil and painted over with oil paints.
- Wooden plates with artificially made delaminations in the ground layer (represented by a layer of gesso). Two kinds of plates were analyzed – with and without paint layers atop the ground layer.
- An oil painting on canvas.
- A wooden based icon.

4.1. Canvas patches

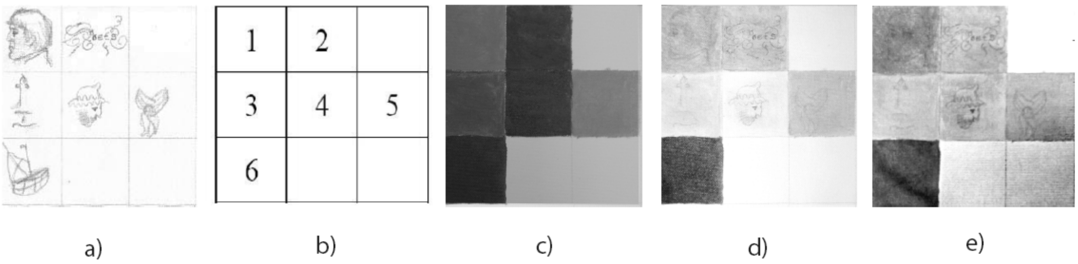

Fig.2. *Canvas patches. a) Pentimenti scheme; b) Patch numbering; c) Visible image; d) Near-infrared image; c) Thermal image after flash application.*

The canvas samples analyzed represented six squares with simulated pentimenti drawn with lead pencil. Each of the squares was covered with an oil paint (1 – golden ochre, 2 – ultramarine, 3 – cerulean, 4 – madder red, 5 – ochre, 6 – Van Dyke brown) (Fig.2).

The NIR images of the canvas samples show the easily-observable contours of the graphite sketches made at the preparation stage. The only patch that appears very dark and does not show the presence of under-drawings is Patch #6. This is not too surprising, since the pigment covering it (Van Dyke brown) which contains lignite and is rich in carbon effectively hiding the graphite sketches from detection. The same results were collected with thermography (Fig.2e). Advanced thermographic methods (PPT and PCT) were not conducted on these samples.

4.2. Wooden plates with defects

Four wooden plates 15 cm ×14 cm in size were used in order to test the ability of the methods to find subsurface defects. Each of the plates was covered with a layer of gesso deposited on the wood substrate and covered with animal glue according to the general procedure used in the creation of panel paintings [2]. The absence of the glue in particular regions caused the delaminations in the drying stage. Two of the plates had a simple gesso layer on top of the wood, the white surface was then darkened with lamp black (Fig.3, Fig.4), while the other two plates had paintings created with oil paints and covered with varnish (Fig.5, Fig.6).

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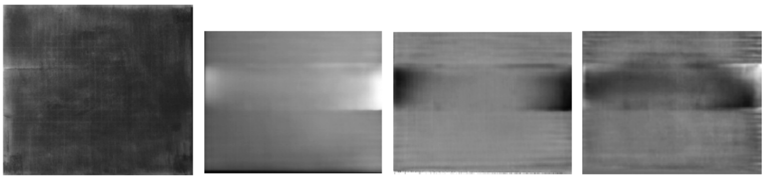
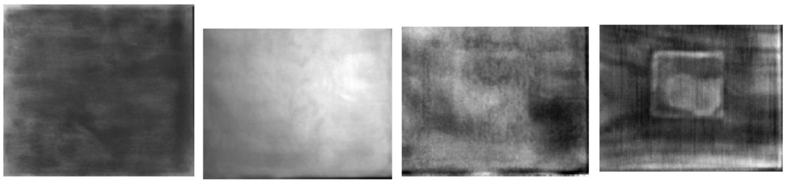


a) b) c) d)

Fig.3. *The first gessoed plate tested. a) Near-infrared image; b) Thermal image after flash application; c) PPT image; d) PCT image.*

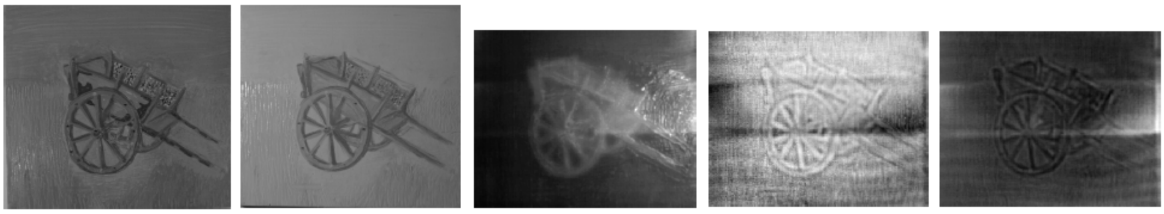


a) b) c) d)

Fig.4. *The second gessoed plate tested. a) Near-infrared image; b) Thermal image after flash application; c) PPT image (the square contours of the detachment are poorly visible); d) PCT image (the detachment is clearly observable)*

As can be seen from Fig.3a and Fig.4a, NIR was not able to penetrate through the thick layers of ground. In its turn, PT correctly indicated the presence of a bar-shaped detachment (Fig.3b). The application of PPT and PCT techniques improves the contrast of the image and allows for the visualization of wood grain(Fig.3c-d).

The second of the two gessoed plates represents an interesting example when PT does not determine the presence of delamination. PPT applied to the data located the defect, but still provided a noisy image (Fig.4c). In turn, PCT created an excellent image of the defect (Fig.4d), the PCT allowed for creation of an image that was better than PT and PPT but for this only the higher principal components (5^{th} and 6^{th}) were retained. This underscores the importance of the image processing techniques for the aids of precise thermographic analysis.



a) b) c) d) e)

Fig.5. *The first model panel painting tested. a) Visible image; b) Near-infrared image; c) Thermal image after flash application; d) PPT image; e) PCT image.*

a) b) c) d) e)

Fig.6. *The second model panel painting tested. a) Visible image; b) Near-infrared image; c) Thermal image after flash application; d) PPT image; e) PCT image.*

Nearly the same situation is observed with the painted wood plates (Fig.5, Fig.6). In both cases PT images provided low-quality images with barely visible contours of the defects (Fig.5c, Fig.6c). PPT allowed for higher quality image revealing the delamination more clearly, though in the second case the contours of the defect were obstructed by the drawing itself and barely visible (Fig.6d). Using PCT it was again possible to find the contours of the defects more distinctly.

4.3. Oil painting on canvas

Two oil paintings were analyzed for the presence of defects and pentimenti with application of the same techniques. The analysis of the first portrait of a Victorian Lady with NIR increased the brightness of the background and highlighted the retouched region in the upper left corner of the painting (Fig.7b). No pentimenti were found.

PT revealed an unexpected feature – a cross on the neck of the Lady in the portrait (Fig.7c). Apparently the cross was made with a pigment different from that used for the jacket so the difference in their thermal properties resulted in an observable thermal contrast. Surprisingly, PPT provided a noisy image impossible to interpret, while PCT did not offer much improvement in respect to PT image.

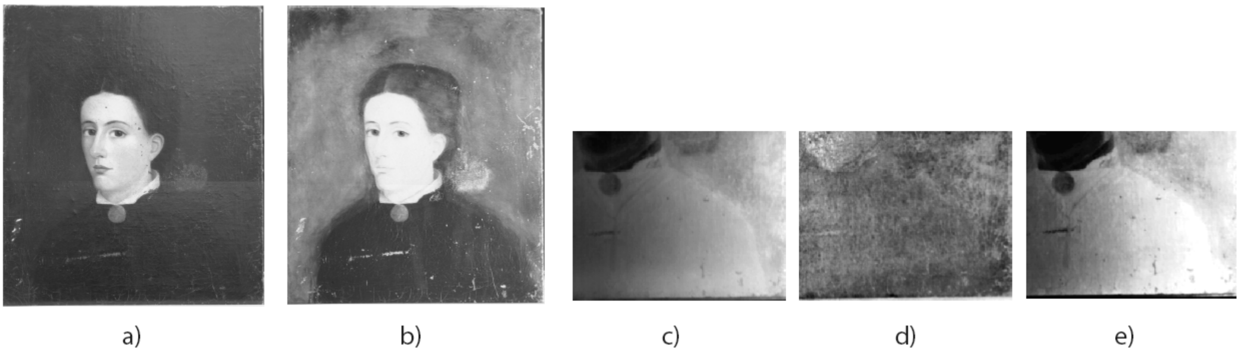


Fig.7. *An oil-on-canvas portrait tested. a) Visible image; b) Near-infrared image; c) Thermal image after flash application; d) PPT image; e) PCT image.*

In the NIR image of the second painting, "The Musician" (Fig.8b) distinguishable thin sketches can be seen. The shape of the sketches allows for the conclusion that they were drawn in the preparatory stage of the painting when the artist was laying out the composition of the work. When sketches of this quality are found it contributes to the opinion that the painting is an original work.

PT and PCT images (Fig.8c, Fig.8e) exposed the same sketches while PPT again was hard to interpret.

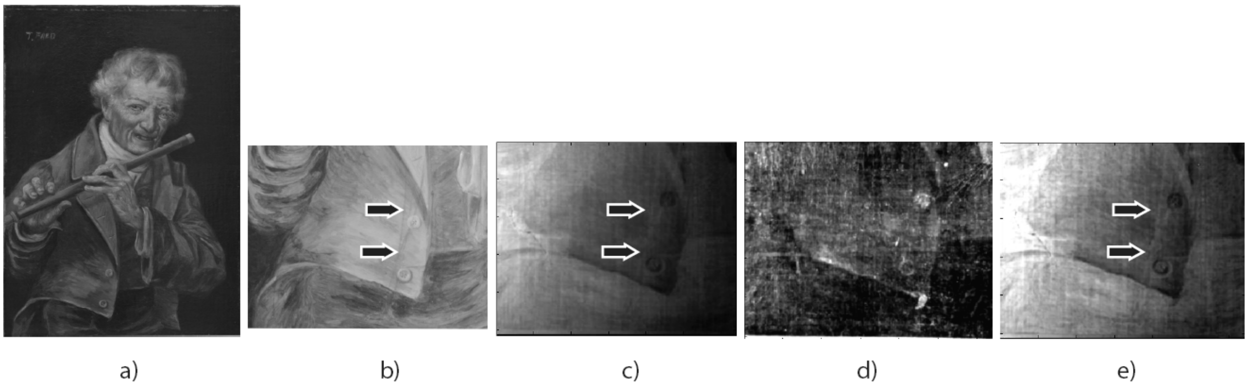
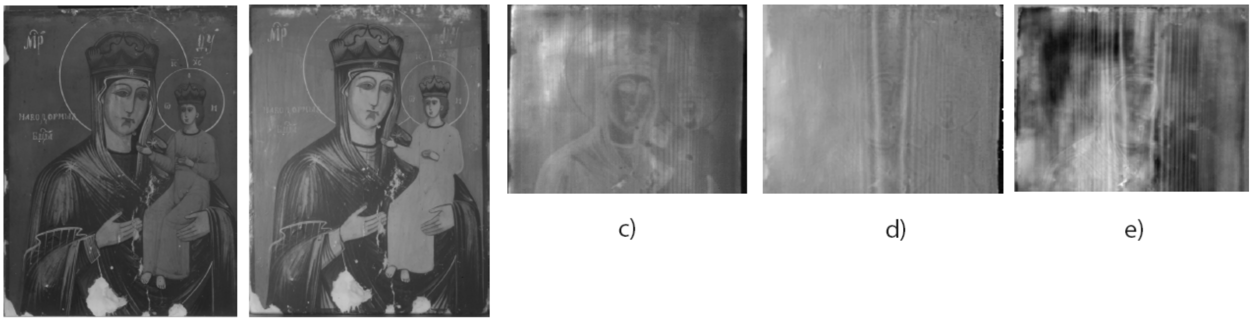


Fig.8. *An oil-on-canvas portrait tested. a) Visible image; b) Near-infrared image of the lower part of the painting (the graphite sketches are shown with arrows); c) Thermal image after flash application (same sketches are visible); d) PPT image; e) PCT image (the sketches are shown with arrows)*

As an example of a wood-based painting an icon from 17th century was used (Fig.9a). The icon has some deformation of the base due to the drying, which lead the authors to conclude that there was the presence of possible delaminations inside the wood. PT confirmed the presence of delaminations in the top left corner of the icon (Fig.9c) as well as made visible the structure of the wood. PPT displays the wood grain better, though the delamination was not as clearly defined. PCT happened to be a perfect way to visualize both the wood grain and the delamination itself (Fig.9e). It is worth of note that the edges of the defect are not as sharp as in the case of simulated hollows before. This may be caused by the fact the blind detachment becomes thinner near its edges.



c) d) e)

a) b)

Fig.9. *The wood icon tested. a) Visible image; b) Near-infrared image; c) Thermal image after flash application (some hollows in the wood base are visible in upper left part); d) PPT image; e) PCT image (the delaminations in the wood are well observable in the upper left corner)*

Conclusion

Several samples simulating canvas- and wood-based artworks were tested with near-infrared reflectography and compared to the results of thermographic inspection.

It can be concluded that while near infrared is suitable for the purposes of locating pentimenti, thermography exhibits high sensitivity to the defects present and helps in visualizing them. At the same time it was found that thermographic analysis appears to be suitable for the same purposes as near infrared, namely, for finding areas which were over-painted and sketches made with graphite. The presence of the foreign materials under the surface of the painting result in high enough surface temperature changes that they can be detected with the thermal imager.

Also it is worthful to highlight the usefullness of the image processing techniques which allowed for improving the images acquired under express tests (PT) and resolving the contours and shapes of defects with higher contrast.

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