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Infrared vision applications for the nondestructive testing of materials

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Abstract

Infrared vision for the nondestructive testing (NDT) of materials has considerable grown in the last few years thanks to progress in the detectors technology and computers, and to the implementation of advanced signal processing techniques. Typical applications can be divided in two major groups. On one hand, there is the near (NIR) and short-wave infrared (SWIR), which are commonly employed for the assessment of artworks (e.g. paintings and frescoes) since some painting pigments are semi-transparent to the infrared on this spectral bands and some other are not (e.g. carbon based). Hence, this can be conveniently used to detect underdrawings and other features in the first few painting layers. Recently, NIR and SWIR reflectography and transmittography have been proposed for the inspection of semitransparent composites materials such as glass fiber. On the other hand, there is infrared thermography, which involves the detection of surface and subsurface defects based on the differences in thermal signatures in the mid- (MWIR) and long-wave (LWIR) infrared bands. Infrared thermography has been used for years on the inspection of a wide variety of materials (e.g. concrete, wood, steel, composites, etc.). Furthermore, thermography in the MWIR/SWIR has shown interesting complementarities to NIR/SWIR reflectography for the inspection of cultural heritage objects. In this paper, a review of classical and recent applications of infrared vision is provided and discussed in detail with examples.

Keywords: NDT-wide, Infrared Testing (IRT), infrared vision, reflectography, transmittography, thermography, artworks, composites

1. Introduction

Infrared (IR) vision can be thought as a subdivision of computer vision (i.e. the use of computers to emulate human vision [1]), which employs (low-, mid- and high-level) computerized processes to analyze images generated in the infrared part of the electromagnetic (EM) spectrum. To "analyze images" is of course a very wide concept, which depends not only on the user's goal (noise reduction, contrast enhancement, segmentation, etc.) but also on the way images are generated (a single image, a feature evolution on a static scene, a dynamic sequence, etc.). As can be seen from Figure 1 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.

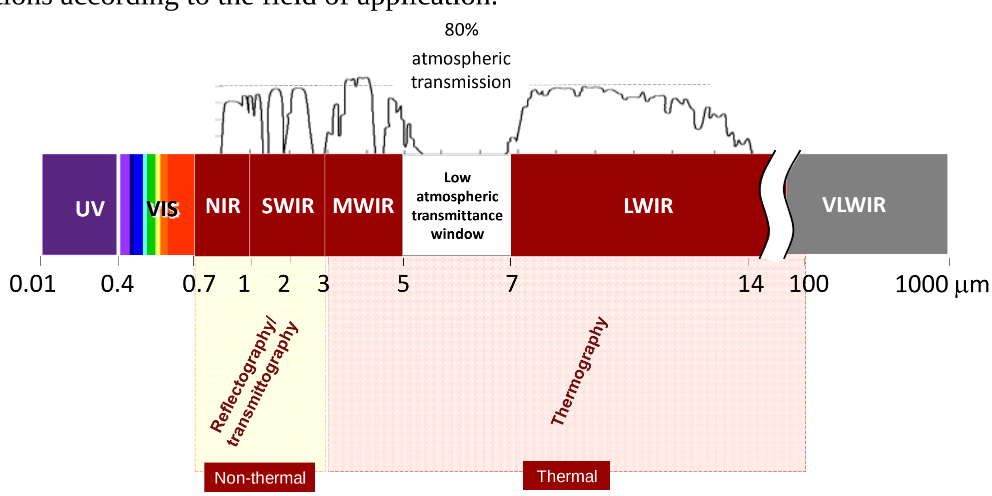


Figure 1. The infrared bands in the electromagnetic spectrum.

Figure 1 proposes one of such classifications that takes into account the atmosphere high transmission windows and the type of detectors being used. Four IR spectral bands are of interest for infrared vision applications: (1) the near infrared band (NIR, from ~0.75 to 1 μm), (2) the short-wave IR band (SWIR, from ~1 to 2.5 μm), (3) the mid wave infrared (MWIR, from ~3 to 5 μm), and (4) the long wave infrared (LWIR, from ~7 to 14 μm).

An additional and important distinction can be made between them: the NIR/SWIR bands can be considered as non-thermal forms of IR radiation, similar to radiations in the visible spectrum (light), whilst the MWIR/LWIR bands are the result of surface thermal emissions and not reflections. These two IR radiation forms are discussed next.

2. Non-thermal infrared vision

Non-thermal infrared vision is based on the detection of near (NIR, from ~0.75 to 1 μm) or short-wave (SWIR, from ~1 to 2.5 μm) infrared radiation reflected from (reflectography) or transmitted through (transmittography) the object of interest. Proper selection of a continuous and uniform active illumination source is a critical part of a non-thermal inspection system. For instance, incandescent lamps provide a wide electromagnetic (EM) spectrum, going from the ultraviolet (UV, from 0.01 to 0.35 μm) to the very long wave infrared (VLWIR, from 14 to 1000 μm), see Figure 1 for reference. Fortunately, a vast part of the radiation from such a source is in the visible and the NIR and SWIR spectral bands, and therefore, it can be used as an illumination source. On the contrary, the EM spectrum of fluorescent lamps is narrower and with a few distinctive high intensity peaks mostly in the visible spectrum [2]. Radiation in the NIR/SWIR spectrum is very limited and can hardly be used as a reliable illumination source. Light emitting diodes (LED) are an example of a very interesting illumination source since they provide a narrow spectrum at specific narrow wavelengths, from UV to VLWIR including NIR/SWIR [3]. The radiation source can be combined with the utilization of narrow-band filters to further improve contrast [4].

3. Thermal infrared vision

Thermal infrared vision also known as infrared thermography, is based on the utilization of a mid-wave (MWIR, from ~3 to 5 μm) or long-wave (LWIR, from ~7 to 14 μm) infrared sensors, such as an infrared camera, to acquired thermal images or *thermograms*, from the surface of the object being observed. This can be performed in an *active* or a *passive* manner, i.e. with or without using an external heating (or cooling) source to promote thermal contrast between dissimilar materials. In general, active thermography is of greater interest than passive thermography for the non-destructive evaluation (NDE) of materials since an external thermal stimulation is normally required to detect subsurface defects, although the passive approach has been successfully employed in a number of applications, e.g. aircraft inspection right after landing for water ingress assessment. Active infrared thermography is a well-established NDE technique [5, 6] that allows a fast inspection of large surfaces and is gaining popularity for the inspection of materials. Active heating induce a temperature difference between defective and non-defective areas in the specimen under examination.

4. Experimental configuration

The experimental configuration for non-thermal and thermal infrared vision is similar as illustrated in Figure 2. The radiation source ❶, thermal or non-thermal, is pointed towards the inspected object ❷ in either reflection (same side as the camera) or transmission (camera on the opposite side). The camera ❸, non-thermal or thermal, records images from the object surface. Data (single images or sequences of several images) is stored and processed with a computer ❹.

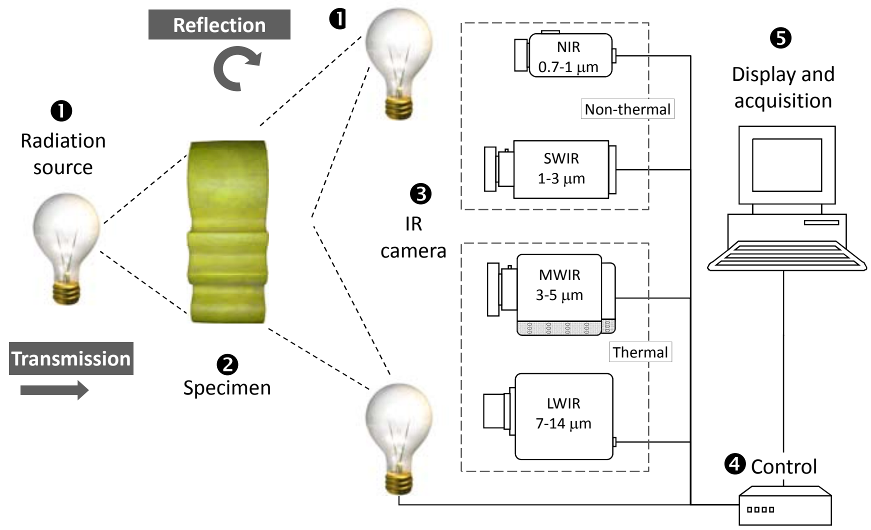


Figure 2. Typical experimental setup for infrared vision.

Figure 2 schematizes the IR vision experimental setup using an optical source, i.e. an incandescent light bulb, which delivers wide spectrum IR radiation covering both non-thermal and thermal applications. In practice however, the illumination or heat sources are carefully selected depending on the application.

Illumination sources such as light-emitting diodes (LEDs) and laser diodes are commercially available and cover several specific spectral bands in the NIR/SWIR spectrum. Alternatively, narrow-band filters can be used in combination to wide spectrum illumination sources.

A wide variety of energy sources are available for active thermal vision, the most common types can be divided into optical, mechanical or inductive, although many other sources can be employed (e.g. hot/cold water/air jets, heating blankets, etc.). There are also different techniques depending on the way heat is delivered to the specimen: pulsed, modulated or lock-in, square (or long) pulse, step heating, and line or point scan. The use of one or the other depends on the specific application. For instance, pulsed thermography using optical sources, e.g. photographic flashes, is often the preferred choice for the inspection of composites for aerospace applications [7], where large surfaces are inspected at once and flaws are relatively large and shallow. On the contrary, lock-in inspection using ultrasounds as heating source would be a better option for the detection of open micro-cracks on thermally sprayed coatings [8], where heating non-homogeneities from optical sources would not allow to detect cracks.

5. Applications

5.1 Near infrared reflectography/transmittography

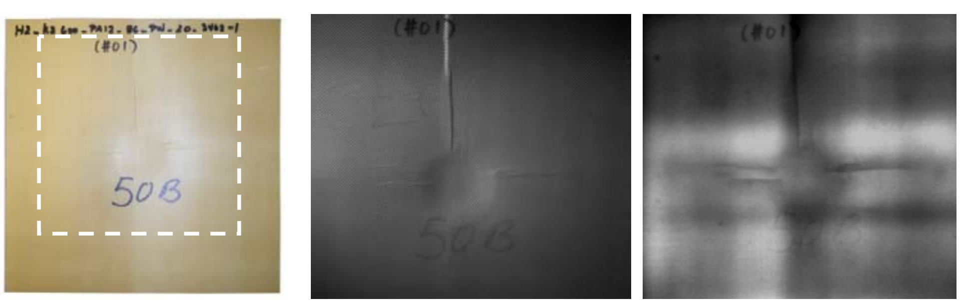
Infrared reflectography for the inspection of paintings is one of the best examples of application for non-thermal IR vision. It has been studied since the 1930s as reported in [9], although the equipment and technique has evolved though the years following extensive improvements in camera, optics and computer technologies. At the beginning, photographic films were used, Vidicon cameras in the 1960s, digital cameras in the 1990s and multi-spectral single-point scanners in the 2000s, which considerably diminish the effects of optical and geometrical non-uniformities with respect to multi-detectors arrays.

Figure 3 presents two reflectograms of a painting. The first one was obtained using a CCD camera (μTech Phoenix PC-1280, 1280x1024 pixels) and a 780 nm LED source. The second reflectogram was obtained with a SWIR camera (Goodrich SU640SDWH-1.7 RT 640x512 pixels, InGaAs)

Visible **NIR (780 nm)** **SWIR (1650 nm)**

Figure 3. Infrared reflectography on a painting.

As can be seen from these images, the NIR reflectogram in the NIR spectrum show some underdrawings not seen in the photograph, for instance the authors signature at the bottom right and a maple leaf at the left. The SWIR reflectogram show these features with better contrast as well as a few others: the inscription "CE" (inverted) above the maple leaf, a sort of bird, a small square, some guiding sketches (on the left and around the neck) the number "75". The use of NIR reflectography/transmittography for the inspection of composites is far more recent [4]. Still, it is very promising for the assessment of composite materials semi-transparent in the NIR spectrum as it is shown in Figure 4, which presents some results from a aramid-phenolic composite (Kevlar) impacted specimen in transmission and reflection modes inspected form both sides.



(a) **(b)** **(c)**

Figure 4. Aramid-phenolic composite impacted specimen inspected with a CCD camera: (a) specimen photograph, (b) reflectogram using a 940 nm source; (c) transmittogram using a wide spectrum source.

The photograph in Figure 4a show a subtle indication of the impact in the front surface whilst the NIR reflectogram in Figure 4b and the NIR transmittogram in Figure 4c show more clearly the damage caused by the impact. The reflectogram provides a good indication about the extent of the damaged area and the transmittogram provides information about the internal fibre distribution (some areas appear lighter than others). Only a portion of the specimen is shown in these NIR results corresponding to the dotted line in Figure 4a.

5.2 Pulsed infrared thermography

Pulsed thermography (PT) is one of the oldest active approaches for infrared thermography [11]. It is often referred as flash thermography since in its classical configuration, a set of 2 (or more) photographic flashes is used to heat the surface of the inspected object. Surface cooling is recorded with an infrared camera. Most of the time, advanced processing techniques are required to improve defect contrast and signal-to-noise ratio and to characterize defects (determine depth, size and thermal properties). One of such processing techniques is pulsed phase thermography (PPT) [12].

The painting in Figure 3a was originally intended for active infrared thermography inspection. The underdrawings discussed in the previous section were a pleasant unexpected revelation. This specimen contains 3 fabricated internal delaminations at different locations and depths as can be seen in Figure 5.

Figure 5. PPT phasegrams of the painting at different frequencies: (a) 0.025 Hz, (b) 0.038 Hz, (c) 0.088 Hz, and (d) defect shapes and locations.

Raw data was processed by PPT. Phasegrams at different frequencies are shown in Figure 5. In PPT, deeper defects are seen at low frequencies and shallow ones at high frequencies. Defect C can be clearly identified from Figure 5a to Figure 5c, which correspond to frequencies ranging from 0.025 Hz to 0.088 Hz. No other defect is visible at the lowest frequency (0.025 Hz), hence defect C is the deepest defect that can be detected. Defect B, being detected between frequencies from 0.038 Hz (Figure 5b) to 0.44 Hz (not shown), is the second deepest defect. Finally, defect A is visible from 0.088 Hz (Figure 5c) to less than 1 Hz (not shown).

Another example of PPT inspection is shown in Figure 6a. This 36 x 13.5 cm^2 specimen having variable thickness as shown in Figure 6b, was made with simulated defects close to real defects, of various depths and several configurations (Figure 6a). The wood is coated with some priming layers, which constitute the basis for the painting. These layers, made of a mixture of gesso and glue, are thinner and more fragile than the support (Fig. 5b). Expansion and contraction of the support due to daily fluctuations of the ambient parameters can produce large strains and eventually cracks in the priming layers, as they become less flexible with age (defects 11, 15).

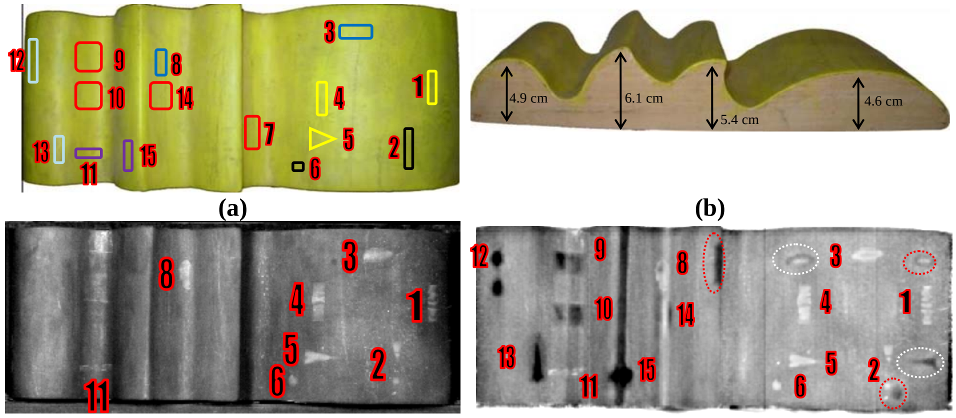


Figure 6. Curved shape wood specimen inspected by pulsed phase thermography: (a) front view showing the map of artificial defects; (b) Raw thermogram at *t*=0.06 s (d). Principal Component Thermography 3rd Component (e), PPT phasegram at *f* = 0.055 Hz (f),

Furthermore, abrupt changes of humidity and temperature or heat exposure may also cause unpredictable stress distributions in the heterogeneous materials of the support (defects 1, 3, 4, 5, 7, 9, 10, 14 in Figure 6a), with consequent damage to the painting. All these mechanisms may lead to the formation of detachments and cracks (defects 1, 11). It is very important to know how the presence of support cracks and discontinuities alter the movements of the painted surface.

In addition, insects can attack wooden artefacts and cause serious damages. During their growth, the larvae make tunnels in the wood; they may become extensive, affecting the panel core without any external signs of damage (defects 2, 6). Defects in painted structures may also be due to intrinsic factors such as irregular wood grain or structural anomalies.

Although it was possible to identify flaws from the raw thermogram in Figure 6d, PPT processing considerably improved defect detectability and was essential to confirm others anomalies created artificially below the layers. The post processing approach was essential, in particular, for defects 9, 10, and 14 simulating loose knots. A similar conclusion can be drawn for defects 12 and 13 concerning a possible machine burn on the wooden support. Only defect 7, situated in a narrow convexity has not been confirmed neither by raw thermogram, PCT, PPT or NIR reflectography. Furthermore, real defects were identified both by PPT and circumscribed by a white dashes circles (Figure 6d).

6. Conclusions

Infrared vision, thermal and non-thermal, is a very promising technique that is still finding new and interesting applications. A great variety of materials have been successfully inspected by infrared thermography for years. Besides traditional applications for artworks inspection, NIR/SWIR reflectography/transmittography open a new area of research for the inspection of semi-transparent materials such as composites (Kevlar or GFRP). Active thermography has already a solid background in the NDT of several materials. Advanced thermographic signal processing is an active research area, which provide a valuable tool to improve signal-to-noise ratios and defect contrast.

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