INFRARED REFLECTOGRAPHY USING 3D LASER SCANNING

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A 3D laser scanning instrument, equipped with an optical transmitter containing a continuous 785 nm diode laser, was used in order to obtain infrared reflectography data of oil paintings. The investigation was carried out in two modern oil and acrylic paintings on canvas and a late 16th century panel painting. In the first case results were compared with existing documentation of the artistic process and in the second with a previously elaborated study by IR reflectography. Data recording took as short as five minutes, providing an IR image comparable to those obtained by reflectography in the IR-A zone of the spectrum. The technique additionally provides high resolution topographic data of the artworks' surrounding, such as frame and adjacent walls, and has potential to be developed into an alternative method for investigation of pigment layers on virtually any surface, especially if these are of great dimensions or almost inaccessible.

Introduction

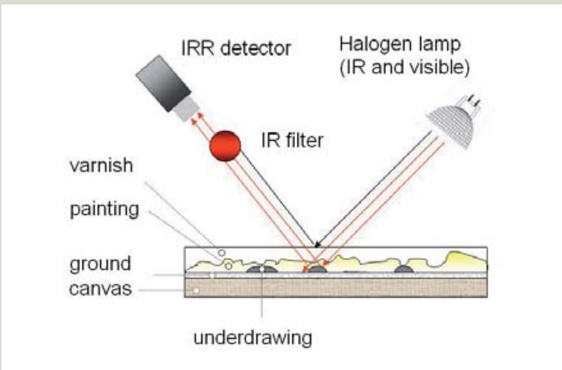
Infrared radiation is situated within the electromagnetic spectrum just past the red segment of visible light and before the microwave region. Generally, the IR spectrum is divided into IR-A (700-1400 nm, near-infrared), IR-B (1400-3000 nm) and IR-C (3000 nm - 1 mm). Unlike visible light, infrared radiation penetrates somewhat into the layers of a painting, depending upon the pigments, varnishes and other materials used during its execution. Backscattered light therefore contains information about deeper paint layers, underdrawings and canvas state. In particular, making visible the compositional sketches, normally done using charcoal and applied on the preparation layer prior to the use of paint, but also signatures, dates, inscriptions or monograms hidden underneath the painted surface layer, provides to the professional valuable information that can help to assign authorship, track back the creational process and detect changes in the painter's original intentions (known as "pentimenti") [1].

The first attempts to exploit this technique for art and restoration purposes began in the 1930s, when suitable film material became commercially available. Infrared photography was limited to the real near-infrared, a range approximately between 700 nm and 900 nm. Modern infrared reflectography (IRR), a commonly used and non-destructive technique for the investigation of ancient paintings, makes use of digital cameras, whose incorporated CCD sensors are inherently sensitive to infrared light, in that way images with a wavelength from 800 nm to 2000 nm may be obtained [2].

The instrumental setup of an investigation employing IRR is depicted in figure 1.

The best contrast is obtained when opaque pigments that are transparent for the infrared light, such as lead white, have been used in the painting. In this case, the infrared radiation passes through the pictorial film until it hits either a black carbon pigment of the underdrawing, where it is absorbed, or the adjacent ground layer, often made of white

Figure 1. A typical instrumental setup for IR reflectography. The red lines indicate infrared (IR) while the black lines indicate visible radiation (VIS).



gesso (calcium sulphate), where it is backscattered. The result is a picture of black areas (absorbed light) over white background (reflected light).

IRR is nowadays widely accepted and used as a valuable tool for the investigation of drawing constituents [3], but can also be applied to obtain information on pigments on supports other than canvas or wood, such as mural [4] and cave paintings [5]. Often, IRR recordings are overlaid to visible (VIS) measurements to produce false colour infrared composites, normally generated by plotting the green parts of an image as blue, the red parts as green and the near-infrared data as red, providing additional information on pigments, varnishes and binding media. Recent developments tend to use integrated approaches, such as combining data obtained by IRR with thermography [6], X-ray fluorescence or colourimetry [7].

A main drawback of IRR is the time consumption necessary for manually mounting many mosaic pictures, using dedicated software. This is particularly true for paintings of great dimension, where scaffolding has to be constructed for the investigation in situ, because the camera has to be positioned relatively close to the artwork. Accurate x-y translation of the painting on a plane perpendicular to the camera is also difficult due to geometrical and photometric distortions. Finally, a uniform illumination by the lamps is also not always easy to achieve.

A wide range of laser techniques are nowadays commonly used for heritage applications [8]. Upon the laser power applied, they may be divided in three categories: (a) high power applications that may be considered somewhat destructive, normally using Nd:YAG lasers, such as laser ablation for diagnostic [9], cleaning purposes [10] or laser-induced breakdown spectroscopy [11]; (b) others use moderate laser power but still high enough to produce excited states of the investigated species, such as Laser Induced Fluorescence [12] or Raman Spectroscopy [13]; (c) and on the low end of applied laser power, holographic interferometry [14] and laser scanning. Laser scanning is nowadays frequently used, typically for producing three dimensional models of historical sites [15] and caves [16], or to produce real time topographic data for documentation of excavations.

The task of such instrument is to assign to each point reflecting a laser beam within its range of operation X, Y, Z coordinates, producing a so called point cloud, which is the raw data for subsequent modelling. This task can be achieved in two manners. On one hand a pulsed laser can be employed, measuring the round-trip time of the pulse (time-of-flight, TOF), which is the most widely used technique for long distance measurements (meters to kilometres). On the other hand, continuous-wave lasers can emit at varying modulation lengths and detect the phase-shift of the reflected signal, from which the distance to the reflecting object can be calculated. When compared to the TOF technique, the phase shift technology considerably speeds up the registration. In our particular case, 120,000 points/second can be achieved with high accuracy, compared to about 4,000 points/second by TOF, although this technique is not appropriate for very long distance measurements such as airborne scanning. Modulated light also allows the scanner to ignore light from sources other than a laser, hence interference is substantially reduced.

The scanner works by sending a light beam into the centre of a rotating mirror. As shown in figure 2, the mirror deflects the laser on a vertical rotation around the environment being scanned. After interacting with the object, the beam is reflected back into the mirror and the phase shift of the wave is measured. Using encoders to simultaneously record both the mirror rotation and the horizontal rotation of the scanner, X, Y and Z coordinates of each point can be calculated.

However, phase shift technology is more susceptible to effects caused by phenomena other than total reflection of the incoming beam on the surface to measure. This undesired effect is studied in the present work in order to obtain infrared data of painted artworks making use of a three dimensional laser scanner emitting at 785 nm and equipped with phase shift detection. Colour information for each scanned data point was simultaneously obtained, making use of a digital camera coupled to the scan head of the instrument.

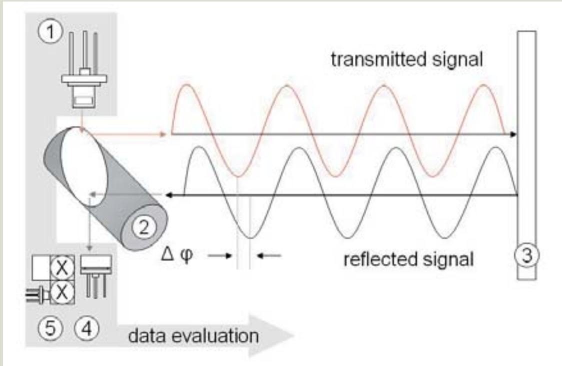


Figure 2. Instrumental configuration for a laser scanner with phase shift (Δφ) detection. Legend: 1 - laser diode; 2 - rotating mirror; 3 - target; 4 - photodiode; 5 - reference oscillator and phasemeter.

Artworks

Studies were carried out on three different paintings. The first, an oil painting on cardboard covered with cotton, is a modern interpretation of Melozzo da Forlì's "Music-making Angel", by A. Criado Portal (2010). The second is an untitled work, painted in acrylic on canvas, showing geometrical forms with underlying drawing, made with charcoal. This painting was made in 2009 as a reference object for IRR studies at the Faculty of Fine Arts of the Complutense University. The third dates to the late 16^{th} or beginning of the 17^{th} century and shows Saint Mark the Evangelist together with his symbol, the lion. This painting, of unknown authorship, belongs to the church of Bujarrabal (Guadalajara, Spain) and is currently being restored at the Faculty of Fine Arts of the Complutense University. It is painted on a wooden panel and attributed to the Castilian School. Figure 3 shows photographs of these paintings.

Instrumental

The 3D laser scanner used was a Faro Photon 80 with software Faros Scene V4.6 for scan control and data evaluation. Colour option was provided via a Nikon D300 digital camera with AF Fisheye

Figure 3. Studied artworks and their respective dimensions. From left to right: Music making Angel, 28x33 cm; Untitled, 38x46 cm; and Saint Mark the Evangelist, 65.5x89.5 cm.

lenses (Nikkor de 10.5mm 1:2.8G ED), mounted in horizontal position above the scanning unit. In order to pinpoint the exact position of the artwork under investigation with respect to the instrument, first a 360º low resolution scan was carried out. Scans were then taken for selected areas in full resolution (0,009° vertical, 0,00076° horizontal) at a recording speed of 120.000 points/second. Finally, the camera was moved to the mirror position of the scanner and referenced optical images were taken.

The instrumental setup used for IRR consisted in a Hamamatsu InGaAs camera (Mod. C10633-23), providing high sensitivity in the wavelength range from 900 to 1700 nm. The camera was connected to a real-time monitor via the standard video output. Connection to a PC went through a standalone video image processor (C2741-62), allowing shading correction, contrast enhancement, averaging, Y-correction and edge extraction. For image capture, the paintings were illuminated using two 100 W halogen lamps.

Results and Discussion

The performance of the instrument matched the expectations, taking into account the rather limited part of the IR spectrum under observation. In general, it can be observed that clear colours tend to gain transparency and the grey scale becomes uniform, revealing several details which have been corrected by the painter in the last stage of the work. In the picture of the angel, a white pearl, initially forming part of the ornamental headband worn by the angel, but finally overpainted, can be clearly distinguished, as shown in figure 4. In the centre of the same figure, in the area just above the marked arrow, tracing details of the angel's hairstyle which have also been slightly changed in the final version can be appreciated. The same applies to the eyebrow and horizontal

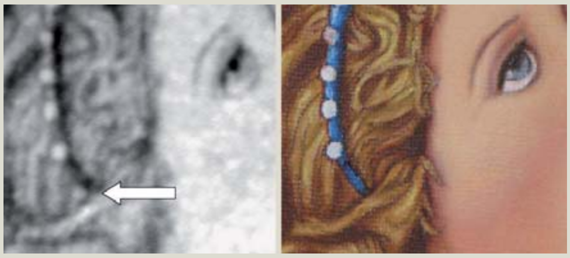


Figure 4. Comparison of IR (left) and VIS (right) images. The arrow indicates a pearl which is not part of the final design.

diameter of the angel's eye, which appear to have different angles and size, respectively, when compared to the finished work.

However, charcoal sketches drawn directly onto the support lack sufficient resolution and have to be more deduced than detected, as shown in figure 5, in the example of the untitled picture. In this case, the underdrawing shows a sitting man with head and beard, which can be clearly distinguished in the reflectography image. In contrast to that, the inner light and dark orange coloured geometrical figures of the original have not become completely transparent in the scanned image, in particular the darker one, superimposing the underlying drawings. This is not surprising as penetration depth of infrared radiation increases with growing wavelength. Obrutsky *et al.* presented a very illustrative example for this fact [17], where a picture showing a horse head was subsequently investigated in the visible, IR-A, IR-B and IR-C region. The longer the wavelength, the clearer two horses in the background could be distinguished, which formed part of the original painting but were finally overpainted by the artist. Nonetheless, the first traces of the charcoal drawings, such as the lower border of the left arm and other features delimiting the figure, already appear using near infrared light, as shown at some details highlighted in figure 5A.

Hence, it is desirable to dispose of alternative laser wavelengths, for example at 1400 nm and

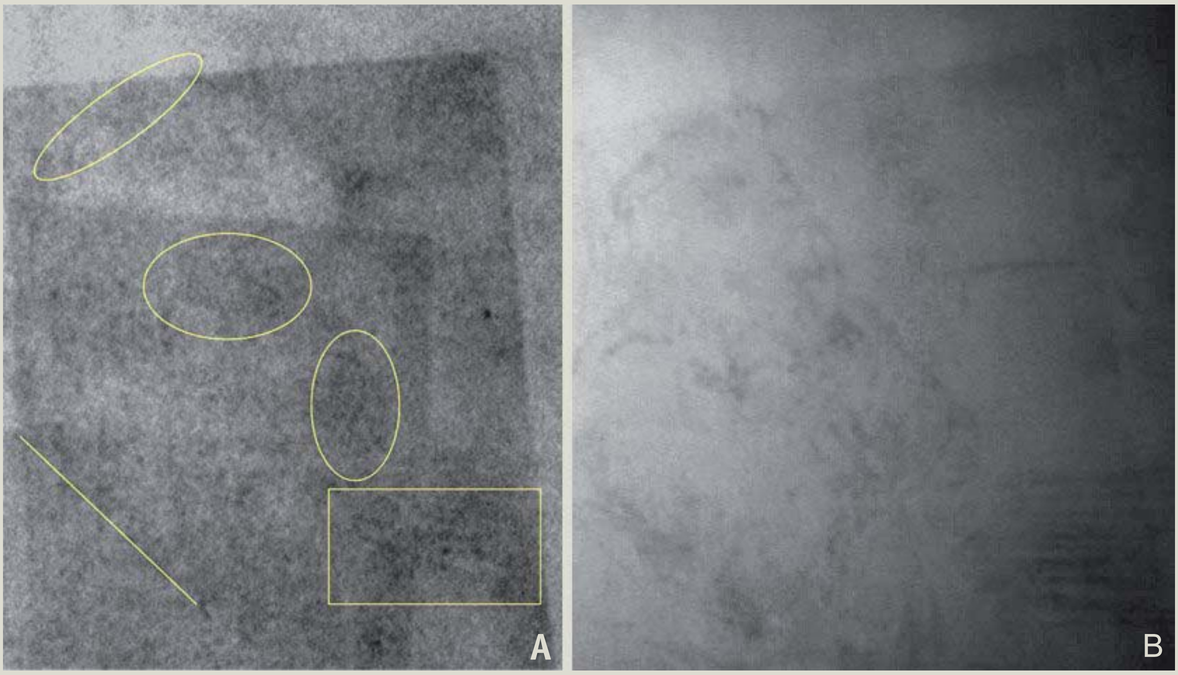


Figure 5 (above). Detail of scanned (A) and IR reflectography (B) image on the untitled painting. In the first image, the upper circle contains a hat, the middle circle shows a right hand supporting the head, the lower circle has a left elbow, the oblique line shows a right arm, and the rectangle contains some horizontal lines.

Figure 6 (below). Colour photography (A), scanned (B) and reflectography image (C) of the lion belonging to the painting of Saint Mark the Evangelist.

2200 nm, for which suitable laser diodes are available. Necessary changes within the laser head would be relatively easy to achieve, for instance by a movable mirror focusing light emitted by the additional diodes into the optical path of the original. From the detector side the issue is a bit more complicated, as the phasemeter has to be set to the changing wavelength, which possibly may be done by hardware changes and/or corresponding software correction algorithms.

Taking into account the instrument's current restriction to a specific wavelength in the real near infrared region (785 nm), the gained information is still highly valuable, although not as complete as an IRR image, which covers the whole infrared region.

This may be highlighted with a comparison of scan and IRR data obtained from the painting of Saint Mark the Evangelist. The underlying sketches, probably done in oil paint rather than charcoal, reflect almost entirely the final composition of the painting, outlining the figures and landscape which were later on filled with colour. Looking into the reflectography data, this becomes particularly evident in zones like the hand of the saint holding the paint brush and the clothing he wears (data not shown). As it can be seen in figure 6, showing a detail of the lion, Saint Mark's symbol, situated in the lower left corner of the panel, generally the more profound paint layers, such as traces of the forehead of the animal, can be distinguished more clearly making use of the IRR image. In turn, details of the superficial paint layers, such as the final touches to improve the appearance of the eyes, can be more clearly appreciated in the near infrared zone, corresponding to the scanned image, as shown in figure 7.

The ultimate compositional features, such as lion's beard, can be confirmed by both methods, as the last paint layers are the first to become transparent using infrared light.

The only problem encountered during data recording is the total reflection of the IR beam, occurring to a certain amount when hitting the painting close to the right angle, causing plain white zones in the image. To overcome this, the artwork has to be situated slightly above or below the optical path of the scan head.

The laser scanner used splits the beam into 3 component parts, operating on 3 different modulation lengths, providing an accuracy of 0.58 mm within the specific range of the measured target, with a vertical and horizontal resolution of 0.009º and 0.00076º, respectively. These can be considered to be very good values for a middle range scanner, nonetheless not enough to reveal very fine details of a painting's topography, such as brush strokes. Furthermore, an additional imprecision is introduced just by the fact that the used IR radiation penetrates into the investigated surface. Nonetheless, a high resolution 3D model of components such as the frame or, in case the artwork is investigated in its original location (e.g. church, cathedral, castle) the paintings' adjacent surrounding, as well as topographic data in case of cave paintings, can be easily obtained from the point clouds recorded during scanning.

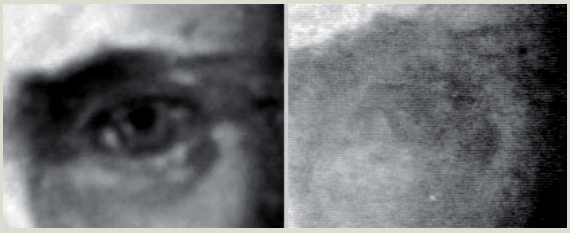


Figure 7. Detail of the lion's right eye obtained by scanned image (left) and IR reflectography (right).

A final issue which may be discussed here is the total amount of radiation to which the painting has to be exposed during the analysis. It is well known that incident light causes ageing processes in pigments and binding media, reason for which preservation of artworks, in particular old and highly valuable pieces always require the limitation of light exposure to a minimum.

The measure of the total power of electromagnetic radiation landing on a particular surface, including infrared, ultraviolet, and visible light, is defined as irradiance, a quantity for which the SI unit is Watt per square meter. The exact calculation of this value for a given light source is not an easy task, but with some simplifications one may get a good estimate of its dimension. Assuming that the source is emitting at a particular wavelength, that neither absorption nor refraction of light occurs in the medium and that the magnetic susceptibility is negligible, irradiance simply decreases with the square of the distance from the source. This is because the overall power is constant but the illuminated area grows squared with distance.

In the case of a directional laser beam, the problem is that the radiation does not distribute uniformly in all directions. During scanning, most of the time a given point at the surface does not receive any energy at all, but a high energy over a short fraction of time, resulting in a low average irradiation but with punctual higher values. The average radiant emittance value for an object situated at a given distance from the scanner may hence be calculated as:

$$I \approx P / 4 \pi d^2$$

where P is the power of the light source and d the distance. In our particular case the laser power is 22 mW and the distance to the artwork was set to about two meters, obtaining an irradiance value of 0.44 mW/m^2. For calculation of short term exposure, we have to use the laser beam diameter, which is, following the manufacturer specifications, a circular spot of about 3 mm diameter at exit. Here we calculate an irradiance of more than 3000 mW/m^2, which is a bit more than the double of sunlight intensity. This peak value will be achieved for the spot area over which the beam passes no longer than the maximum pulse duration of the laser, which is at full resolution 0.0076 seconds only and decreases proportionally with the resolution.

Tungsten halogen incandescent lamps, as those commonly employed for illumination in IRR, are thermal radiators, which means that light is generated by heating a solid filament to high temperatures. Assuming that the spectral power distribution roughly follows that of a blackbody radiator, up to 85 percent of the emitted energy lies in the infrared region of the spectrum, another 15-20 percent falls into the visible and about 1 percent into the ultraviolet wavelengths. The total radiation follows a fourth power law with respect to the tungsten wire temperature, which means that increasing temperature shifts the spectral distribution into the visible region of the spectrum, the area under the resulting bell shaped curve represents the total irradiance.

Under ideal conditions and for the aforementioned distance, for a 100 W halogen bulb we would achieve an irradiance of 2000 mW/m^2 for the total incident electromagnetic radiation, spanning the wavelength region between 200 and 3000 nanometres. Though heat dissipation in air would considerably diminish the real irradiance in the example, in practice these lamps have to be situated much closer to the artwork when taking reflectography images, while the scanner may be placed as far as ten meters from the object without losing much of resolution. Furthermore, one has to consider that the spectrum emitted by incandescent lamps has a considerable amount of light with wavelengths shorter than infrared, which in general is considered to cause more damage to the artwork. This is particularly true for darkening of yellow pigments such as chrome yellow [18], where exposure to UV-light causes superficial reduction of the original Cr(VI) to Cr(III). Possibly the most important factor when comparing both techniques is the total exposure time to light, ranging from tenths of minutes for taking mosaic pictures in IRR to the duration of a laser pulse when making use of scanning technology.
Hence, peak values are in the same order of magnitude for this given example, but for total irradiance, the values obtained for the scanner are about three orders of magnitude lower.

Conclusions

A direct comparison of infrared reflectography versus a 3D laser scanning device for investigation of artworks revealed that both provide comparable information in the near-infrared region. For the mid and far-infrared regions, revealing information of deeper paint layers such as the underdrawing, IRR appears to be the more suitable method, since the laser diodes emission is limited to a well defined wavelength in the NIR zone.

Nonetheless, the scanning technology provides several advantages over classical IRR as coloured and fully measurable 2 or 3D models can be achieved within minutes, even though further modelling, for instance surface topographic analysis and representation, requires additional manpower and computing time. False colour IR pictures are also available, using scan data post-processing in dedicated software. The technique is especially suitable for paintings of great dimensions and with difficult accessibility, as it can be operated from a considerable distance to the object and does not require mounting additional structures, such as a scaffold.

Peak values of light irradiation may be considered to be in the same order of magnitude for both techniques, but much longer exposure times are necessary in case of incandescent lamps, which contrary to the laser, emit a considerable portion of more energetic and hence more harmful light. On the other hand, the overall irradiance for the laser technique is orders of magnitude lower.

The technique has clearly shown potential to be developed into a competitive instrument with respect to IRR. This could be relatively easy to achieve by the incorporation of laser diodes emitting in the mid and far-infrared region into the laser head and the corresponding soft- and hardware changes on the detector side.

Acknowledgments

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