Multi-spectral IR reflectography

Raffaella Fontana*[a], Davide Bencini[a], Pierluigi Carcagnì[b], Marinella Greco[a], Maria Mastroianni[a], Marzia Materazzi[a], Enrico Pampaloni[a], Luca Pezzati[a]
[a]Istituto Nazionale di Ottica Applicata (CNR - INOA), Largo E. Fermi 6, 50125 Florence, Italy;
[b]Istituto Nazionale di Ottica Applicata (CNR - INOA) – Sez. di Lecce, via Barsanti, 73010 Arnesano (LE), Italy

ABSTRACT

A variety of scientific investigation methods applied to paintings are, by now, an integral part of the repair process, both to plan the restoration intervention and to monitor its various phases. Optical techniques are widely diffused and extremely well received in the field of painting diagnostics because of their effectiveness and safety. Among them infrared reflectography is traditionally employed in non-destructive diagnostics of ancient paintings to reveal features underlying the pictorial layer thanks to transparency characteristics to NIR radiation of the materials composing the paints.

High-resolution reflectography was introduced in the 90s at the *Istituto Nazionale di Ottica Applicata*, where a prototype of an innovative scanner was developed, working in the 900-1700 nm spectral range. This technique was recently improved with the introduction of an optical head, able to acquire simultaneously the reflectogram and the color image, perfectly superimposing.

In this work we present a scanning device for multi-spectral IR reflectography, based on contact-less and single-point measurement of the reflectance of painted surfaces. The back-scattered radiation is focused on square-shaped fiber bundle that carries the light to an array of 14 photodiodes equipped with pass-band filters so to cover the NIR spectral range from 800 to 2500 nm

Keywords: IR reflectography, multi-spectral imaging, scanning device.

1. INTRODUCTION

Infrared reflectography is one of the most suitable optical techniques traditionally employed in non-destructive diagnostics of ancient paintings[1, 2]. Generally applied to panel, canvas and wall paintings, this analysis can show aspects of a painting underneath the visible surface thanks to transparency characteristics to NIR radiation (0.8 - 2 μm) of the materials composing the paints. The technique consists in irradiating the painting with halogen lamps, and in detecting the back-scattered radiation with a suitable device; the acquired image is called the reflectogram. When performing multi-spectral imaging, radiation is detected within spectral intervals by means of filters or spectrographs. The basic concept of multi-spectral imaging is that differences in material composition of any particular object often become much more apparent when the object is viewed in a wavelength region other than normal visible light. Where two materials might have the same characteristics for the reflection or absorption of light in the visible wavelength region, it is highly unlikely that this is also the case in the infrared region. Infrared analysis is thus able to show any variation during the artwork preparation (the so called *pentimenti*), the underdrawing, the presence of restoration interventions and repainting carried out by means of modern pigments, fills where the original paint is lost, and, generally speaking, the conservation state of the artwork. This technique gives, thus, precious indications both on the realization phases and on the actual state of the artwork; furthermore it helps dating the painting and in some cases it can confirm or deny the attribution to an artist[3].

When a painting is illuminated with a broad-band continuous source (white light), the VIS part of the spectrum is reflected by the paint layer, whereas the IR radiation can pass through it, being reflected by the preparation surface and

*raffaella.fontana@inoa.it; phone +39 055 2308313; fax +39 055 2337755; http://arte.inoa.it

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absorbed by the underdrawing, depending on the materials used.

Underdrawing visibility is a function of the transparency of the paint layers to NIR radiation and of the underdrawing contrast: IR absorption is high when carbon is present in the drawing (charcoal, graphite, carbonaceous pencils and inks), otherwise in presence of iron-gallium inks the underdrawing can be invisible, even if the paint layer is transparent. Reflectivity is high when the preparation is chalk-and-gypsum based. Transparency depends on the composition and depth of the paint layers, and on the radiation wavelength used. Paints transparency generally increases with wavelength: for $\lambda \sim 1.6$-1.7 μm and paint thickness ~ 0.1 mm, nearly all ancient pigment compounds are at least partially transparent.

Infrared reflectography dates back to approximately 40 years ago and it is based upon the fundamental work of Van Asperen de Boer[1, 2], who laid the theoretical and experimental bases for this technique, and introduced the use of a new detection technique in substitution of the older IR photographic film. IR photography[4], applied for painting examination since the 30s, becomes a routinely analysis only twenty years later, at least applied to Flemish paintings dated XV century, where it gives good results in underdrawing reading thanks to the oil medium and the pigments used in the pictorial layer, besides its thin thickness. In Italy the use of infrared photography is limited to the restoration field to single out repainting and restored regions. The first reflectograms realized with a PbS Vidicon camera is then introduced in the 60s by the Dutch fisicist Van Asperen de Boer[5, 6]: this technique that does not necessitate the development of a film and can give the desired result in real time on a screen. Besides that, photographic film sensitivity in the 700-900 nm spectral range produced poor quality images because of the lack of transparency for the most part of pigments (greens and the blues are nearly opaque) whereas Vidicon sensitivity, between 0.9 up to 2.0 μm where nearly all the pigments used in ancient paintings are transparent, allows to analyze underlying features of the paintings in a more effective way. Vidicon camera is still the most widely used device for reflectography because it combines good penetration properties with low price and easy-to-use characteristics. Its drawbacks are scarce light sensitivity, so that measurements request an intense illumination which can induce a detrimental warming of the painting surface; a limited number (some tens) of grey levels that implies a very low contrast in the images; geometrical distortion due to the camera lens and to its intrinsic characteristics. Besides that, to have high spatial resolution images the measured area must be very small (e.g. 10×10 cm^2 to have a resolution of 4×4 $pixel/mm^2$, needed to resolve the finest marks in the underdrawing). The reproduction of a large panel thus requires the collection of several images (more than 100 for 1 m^2) that have to be successively combined in a mosaic. Since the single images are brighter in the centre and darker on the borders because of the non-uniform sensitivity of the detector's area, the resulting reflectogram generally appears tiled, in many cases even after equalization.

It is about 1980 that the use of solid-state devices (CCDs) becomes established. Their use for IR reflectography, thanks to higher intensity and spatial resolution, allows the acquisition of a few tens of points/mm and the image is much more uniform than that acquired by a Vidicon because the geometrical distortion is only due to the camera lens. Nevertheless the reflectogram quality is not meaningfully improved because of a spectral sensitivity limited to 1.1 μm, similar to the one of photographic films.

Special highly-priced CCD devices[7, 8, 9], based on InGaAs or PtSi sensors, make their appearance on the market in the 90s: they strongly improve the visibility of the underlying features being sensitive up to 1.7 μm or 5 μm, respectively. However, a great number of images have still to be collected to reproduce large paintings with high spatial resolution, and image mosaicing needs calibration and cleaning operations due to the non-uniform lighting conditions, the misalignment of images and the distortion at image boundaries[10].

It is in 1990 that the first prototype of scanner based on single-point detection is developed at the National Institute for Applied Optics[11]. This innovative device, equipped with an InGaAs photodiode, is capable of acquiring reflectograms with a spatial resolution of 16 $points/mm^2$ and a tonal dynamic that are unparalleled by other techniques traditionally used for infrared reflectography. Besides that, point-by-point surface sampling assures uniform lighting and entails off-axis -aberration free images[12]. Its performances were recently improved with the addition of a three-channel head for the simultaneous acquisition of the RGB color image, perfectly superimposing the reflectogram[13].

In the very recent years a new scanner for IR reflectography in the spectral band up to 1.7 μm was presented by Consolandi and Bertani[14]. The system is based on an InGaAs focal plane array which automatically scans the image plane of a lens for wide format photography.

A few devices for multi-spectral analysis of paintings in the NIR spectral band have been developed in the last decade[15, 16, 17, 18], and many publications were done concerning optical calibration of multi-spectral images acquired with systems based on extended detectors and interference filters. Such systems typically suffer from some blurring of their channel images. Because the effectiveness of spectrum reconstruction depends heavily on the quality of the acquired channel images, and because this blurring negatively affects them, a method for deblurring and denoising is required[19].

In this work we present a multi-spectral scanner, to be considered as an "upgrade" of the INOA's *old* scanner, for multi-band IR reflectography. Its working principle is based on a point-by-point acquisition of the surface under study, differently from acquisition with imaging detectors where all single elements (*pixels*) are acquired simultaneously. The use of a single sensitive element solves a series of problems with respect to traditional detection systems, such as uniform lighting of the sampled area, chromatic aberration, geometric deformations, non-uniform detector response, luminosity fall-off from the centre to the border of the image due to the lens. Its drawbacks are instrument huge dimensions and weight, and low acquisition rate. When choosing the proper instrument for IR reflectography the following parameters should be considered: instrument price and portability, spectral sensitivity (the wider the spectral range, the more contrasted and rich of details is the reflectogram), spatial resolution, acquisition and processing time for the reflectogram of the whole artwork under investigation. Depending on the aim of the analysis, one is to be enhanced with respect to the other.

2. THE MULTISPECTRAL IR SCANNER

The block diagram of the scanner is shown in Fig.1: the scanning system moves both the lighting system and the collecting optics. This latter is connected to an optical demultiplexer that carries light to a detector array (split into two modules, a VIS spectrophotometer and a NIR spectrometer), and the whole system is computer controlled.

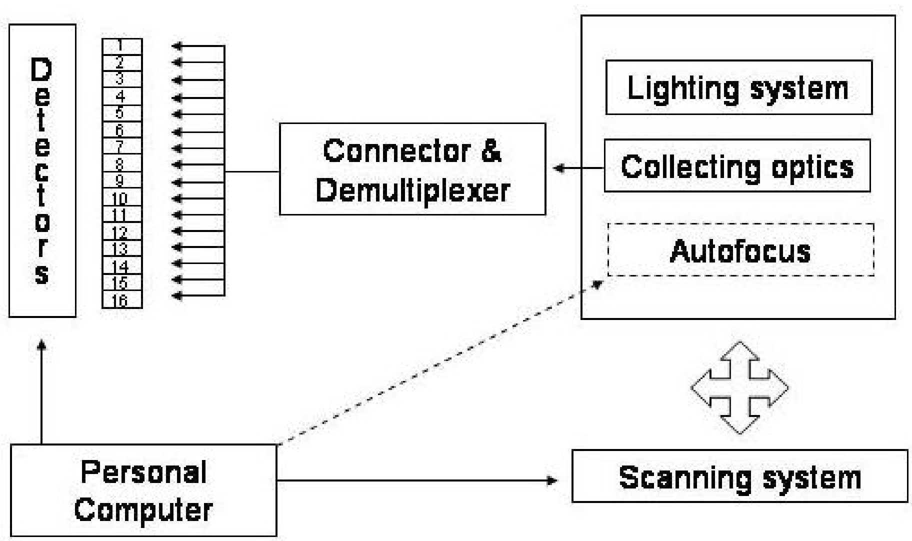
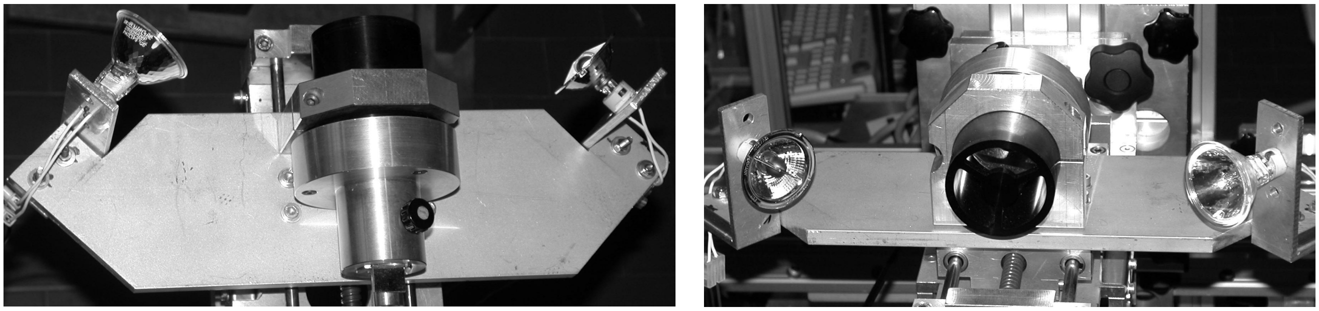


Fig. 1: Block diagram of the multi-spectral IR scanner

Lighting system and collecting optics are placed in a 45°/0° illumination/observation geometry as suggested by CIE for reflectance measurements (Fig. 2).

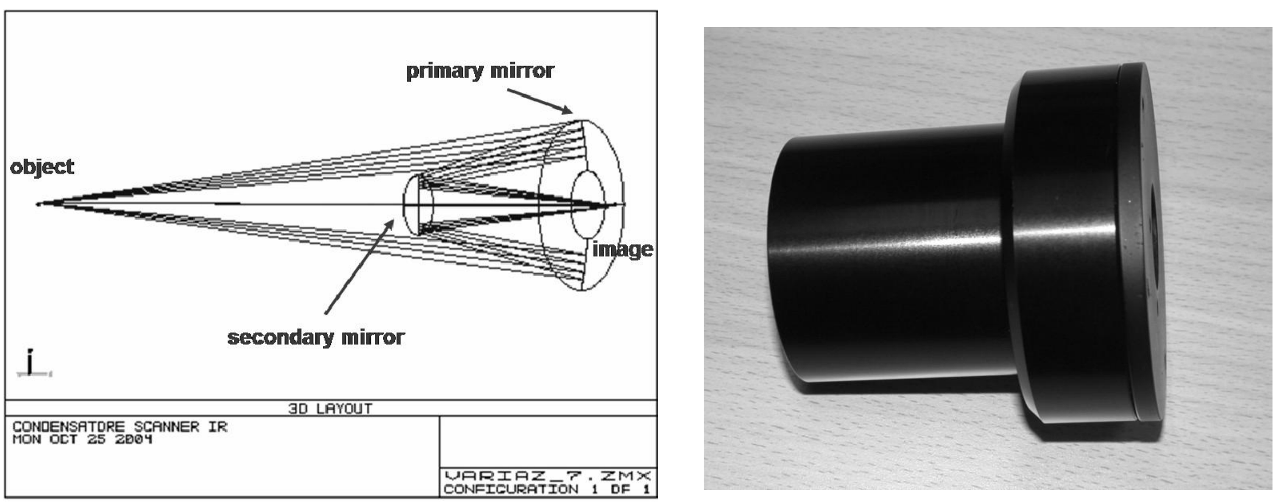
The lighting system is composed of two low-voltage current-stabilized halogen lamps (20 W) irradiating an area of about 5 cm^2. One of them has a 4100 K color temperature in order to enhance the blue emission that is critical when measuring with the visible module, and a dichroic coating transmitting backwards large part of the generated IR radiation, thus minimizing the heating of the painting surface. The other lamp is a standard halogen lamp with an aluminum backreflector. The beam divergence is, in both cases, 10° according to CIE specifications for the 45°/0° illumination/observation geometry.



(a) (b)

Fig. 2: a) Top and b) front view of the optical head, composed of the lighting system and the collecting optics, mounted in a 45°/0° illumination/observation geometry.

The collecting optics (Fig. 3) is a catoptric objective lens made of two faced spherical mirrors (placed at 66 mm spacing; primary and secondary mirror diameters are 50 mm and 17.6 mm respectively) avoiding, thus, the chromatic aberration. The working entrance $f_{\#}$ is 3.7, corresponding to an acceptance angle of less than 16° (according to CIE specifications); the effective $f_{\#}$ is 4.7 because of the secondary mirror darkening. The working distance is about 12 cm with a depth of field of ± 750 μm and a unitary magnification.



(a) (b)

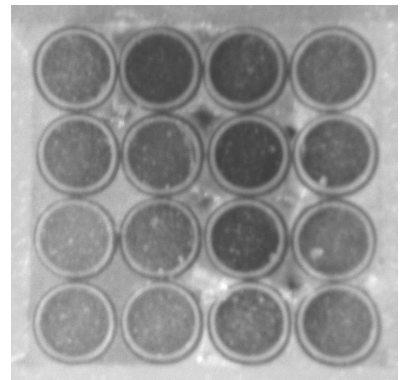
Fig. 3: a) Wireframe image and b) snapshot of the collecting optics.

The collecting optics gathers the radiation scattered from the measured point on the painting and focuses it on a 16-fibers squared-shaped bundle that carries the light to the detector array (Fig. 4). The fiber used is a multimode optical fiber with core and clad diameter of 200 μm and 230 μm, respectively, with transmission in the UV-VIS or VIS-NIR spectral range depending on the module to which it is connected: 14 fibers carry the NIR signals to an array of photodiodes, one of the remaining two is used to carry VIS signals, and the other one will be used either to extend the device capabilities in the UV spectral region or as reserve.

In order to properly align the 16 fibers, a 1 mm groove was dig. The 16 fibers were then stick all together with a two-component glue. The microscope image of the bundle section is shown in figure 4b. The 16-fiber array is not perfectly regular: a fiber displacement of less than 30 μm is somewhere present. We are planning a new technique for the realization of the bundle that makes use of a mask for hosting the fibers, and of plastic rods for keeping them at the right distance.

Fiber light guiding minimizes the load on the scanning system, thus limited to the lighting system and the collecting optics whose simultaneous motion limits surface heating and, together with point-by-point surface sampling, avoids any problem concerning uniform lighting. The termination of the optical fiber bundle is lodged on the image plane by means of a purposely made connector.

(a)



(b)

Fig. 4: a) Fiber bundle and b) microscopic image of its section.

The detection system is a detector array composed of 3 Si and 11 InGaAs photodiodes, each equipped with an interferential filter kept in a filter holder, designed to have the best matching between the detector sensitive area and the fiber. The filter FWHM bandwidth ranges from about 50 to 100 nm, except for the first channel that has a 10 nm FWHM filter in order to match the spectrum obtained with the VIS module. The last channel is wider than the others because of the poor photodiode efficiency in that region. The overall spectral response covers the range from 800 to 2300 nm (the fiber cutoff sets the upper sensitivity limit). In the region beyond 1700 nm, due to the low signal and to the high dark current typical in this spectral region, thermoelectrically-cooled InGaAs sensors are used. These sensors require a heat sink to dissipate the heat generated by the cooler, an amplification circuit and a temperature controller to hold the detector at a constant temperature. The central wavelengths of the 14 channels are resumed in Table 1, together with the bandwidth of the corresponding filter.

CH	1	2	3	4	5	6	7	8	9	10	11	12	13	14
λ [nm]	800	850	952	1030	1112	1200	1300	1400	1500	1600	1700	1820	1930	2265
$\Delta\lambda$ [nm]	10	67	67	55	66	66	90	90	90	90	90	100	112	590

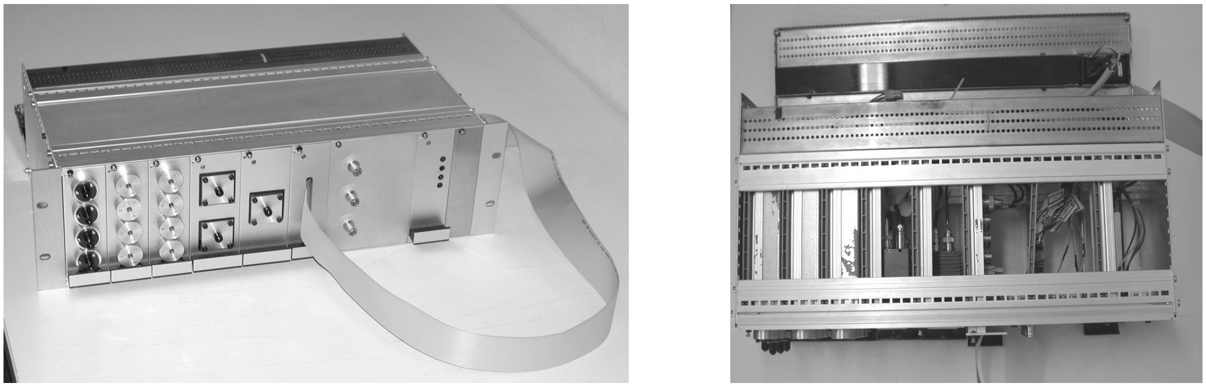
Table 1**.** Central wavelengths and FWHM bandwidths of the 14 channels of the detection system**.**

As the instrument is supposed to be used for *in situ* measurement campaigns, compactness and robustness are important requirements, in order to be easily transported. A purpose-build sub-rack unit (Fig. 5) was then designed to keep all the detectors together. It also comprehends a power supply unit, a pre-amplification and offset circuit, a sample-and-hold board and an ADC (Analog-to-Digit Converter).

The XY scanning system, composed by two high-precision motorized translation stages mounted orthogonally, allows to measure continuously areas up to 1,5 m^2 with a spatial resolution of 16 dots/mm^2. The acquisition time for 1 m^2 area is of about 8 hours at typical acquisition rate of 500 Hz. In the acquisition phase our scanner is probably time-consuming compared with most of existing devices, but this time loss is regained because data do not need neither geometrical nor intensity corrections, and thanks to hardware registration the 14 monochromatic images are automatically superimposed.

The digitized data are recorded and handled via a dedicated software running on a standard PC and can be displayed as 14 monochromatic images. Storing the images in a 8-bit standard format can be chosen either to convert all the grey scale, thus compressing the intensity resolution, or to convert a limited part of the grey scale, to have the highest intensity resolution in selected parts of the image.

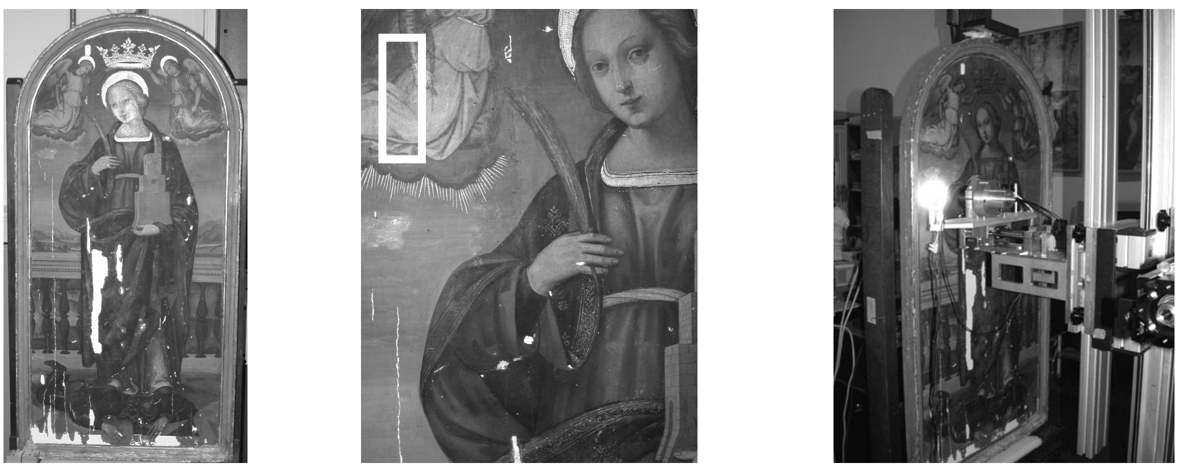
An auto-focus system, besides keeping the painting surface focused during the scanning even in case of irregular surfaces, will allow the simultaneous acquisition of the painting shape.



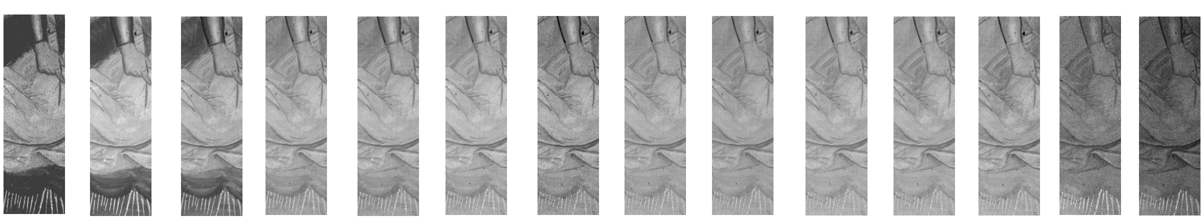
(a) (b)

Fig. 5. Sub-rack unit: a) front view and b) upper view.

Channel equalization was realized on a reference standard surface with a certified reflectance of 40%, and the very first laboratory test were carried out on a painting that is presently under restoration at the Opificio delle Pietre Dure in Florence, where the Art Diagnostic Group has the operative laboratory. 14 multi-spectral images were acquired on a detail of a panel painting of the XV century (unknown Florentine author) and they are shown in figure 6, together with a picture of the painting.



(a) (b) (c)



CH1 CH2 CH3 CH4 CH5 CH6 CH7 CH8 CH9 CH10 CH11 CH12 CH13 CH14

(d)

Fig. 6. Panel painting by an unknown Florentine author: (a) picture, (b) detail of the measured area (white rectangle), (c) NIR multi-spectral scanner during measurements and (d) the 14 acquired images.

3. APPLICATIONS

The first multi-spectral acquisition in the NIR spectral region was carried out on a panel painting by Cimabue (second half of XIII century) representing the Virgin with Child. The painting, that is under repair at the Opificio delle Pietre dure in Florence, was subjected to a series of analyses that are currently part of the diagnostic investigation process. Among all, IR reflectography and color image were acquired by means of the IR-RGB INOA scanner, and the reflectogram and color image are shown in figure 7 and 14a, respectively.

Fig. 7. Virgin with Child by Cimabue (XIII century). a) IR reflectography from 900 to 1700 nm and b) color image.

The 14 monochromatic images were analyzed separately, and pixel-by-pixel differences and ratios between different wavelength images were carried out in order to highlight details that are not visible in the reflectogram obtained with the INOA *old* scanner. A few examples are shown in figure 8, where a detail of the Child's head is shown. In the reflectogram are clearly visible two light spots on the Child's forehead that are present also in the image @ 850 nm, whereas they are absent in the image @2265 nm, where a mark of the golden leaf appears as a white spot above the eye. Considering, for instance, channels number 14 and 2, and making the pixel-by-pixel difference and ratio, all the above mentioned details are clearly visible both in the difference and in the ratio image. Moreover, the decoration in the Child's halo, that was scarcely visible in the separate channels, becomes here evident. In the ratio CH14/CH2 image a mark of a non-homogeneity along the Child's arm makes its appearance.

In figure 9 the detail of the Child's arm is presented: similarly to what happened in the previous example, in the CH2 and CH14 images different spots and retouched regions are evident on the arm and on the hand, and in this latter case the spot is invisible in the reflectogram. Once again, by making the difference and the ratio images all the described details become visible and they are enhanced.

Concerning the information contained in the ratio image, we evaluated the contribution of the different channels in order to emphasize different details. In figure 10 the detail of the Virgin's bust is presented, taking into account the ratio image obtained with channels number 14 and 2, and channels number 10 and 3. In the CH14/CH2 image, for instance, a disuniformity in the Virgin's mantle on the right shoulder is enhanced, whereas dishomogeneities in the mantle on the Virgin's head are highlighted in the CH10/CH3 image, as well as the spots present on the Virgin's face. The complementary information in the two ratio images helps also to study and characterize the big retouch that crosses the painting along its width.

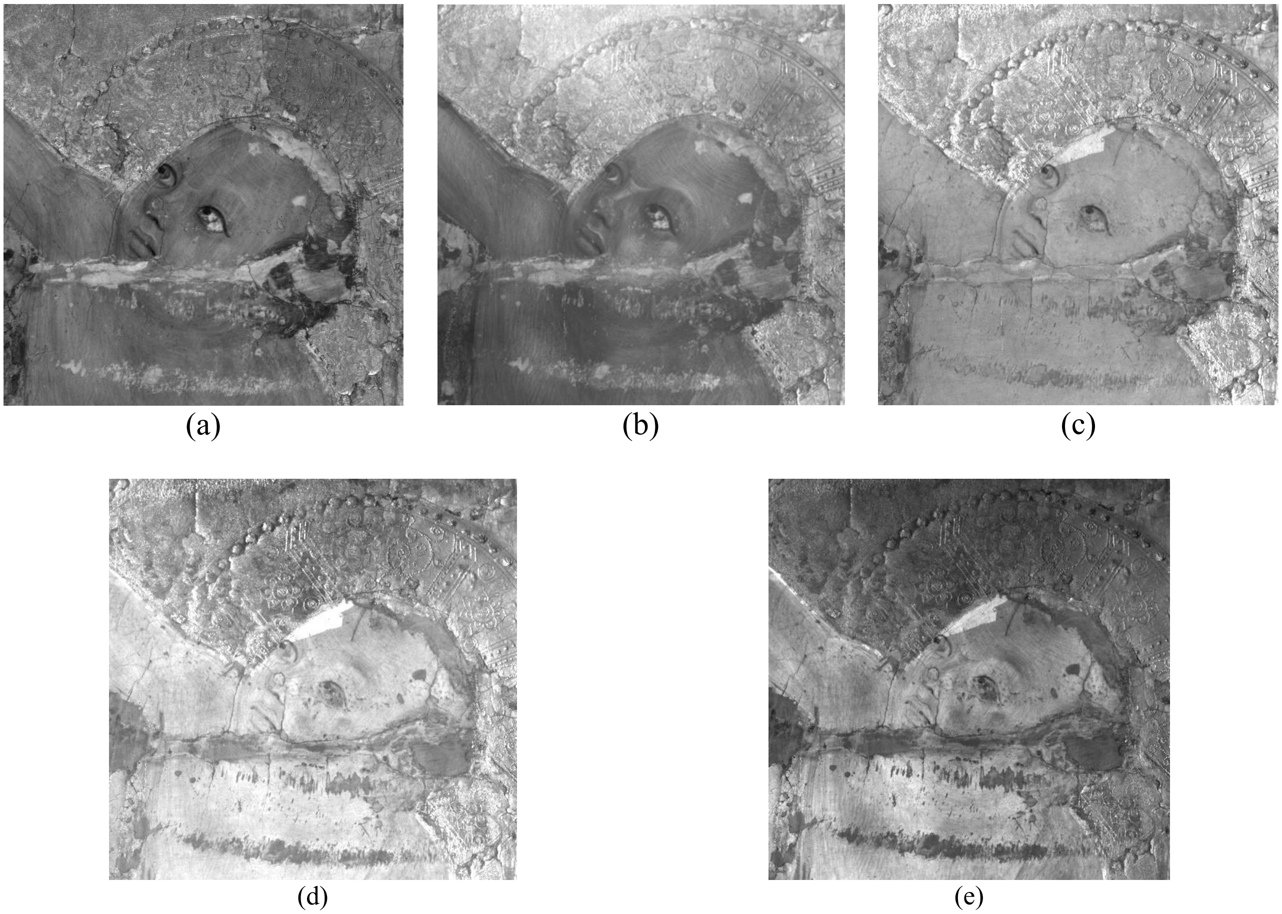


Fig. 8. Virgin with Child (Cimabue), detail of the Child's head. a) Reflectogram obtained with the IR scanner; b) CH2 image @850 nm; c) CH14 image @2265 nm; d) CH14-CH2 and e) CH14/CH2

In order to make somehow automatic the research of hidden details, we applied the Multivariate Imaging Analysis (MIA) that has the great advantage to maintain a visual approach to the multi-spectral data, being thus easy to interpret also for conservators and restorers that are not generally used to manage such an amount of data. In particular, we processed our 14 images by means of the statistical method called Principal Component Analysis (PCA). PCA concentrates significant features into a few representative images, thus facilitating their interpretation. It is a method that describes original sets of data by means of a smaller number of uncorrelated components of progressively decreasing variance. In this case, the collected spectra can be represented by a point in a 14-dimensional vector space. PCA involves rotating the original 14 axes, each representing the original variable, in a new set of axes (called Principal Components), that lie along the directions of maximum variance of the data set, with the constraint that the axes are orthogonal. The variance is maximum on the first axis and rapidly decreases on subsequent axes. PCA reveals those variables, or combination of them, that determine some inherent structure in the data.

Principal Component Analysis was applied on a panel painting by Cosmè Tura (Venetian painter, XV century) representing the Virgin with Child (Fig. 14b). In figure 11 the plot of the loadings P (new set of eigen-vectors) versus the old base (wavelengths) is shown together with the score images T (eigen-values, projection of data along the new axes). For instance, from the plot of the first loading it comes out that in the PC1, all the wavelengths give the same contribution, whereas the low-wavelengths and high-wavelengths are highlighted by the PC2 and PC3. The decreasing information contained in the score images is, from T1 to T4, 91.9%, 5.5%, 1.9% and 0.3%, respectively.

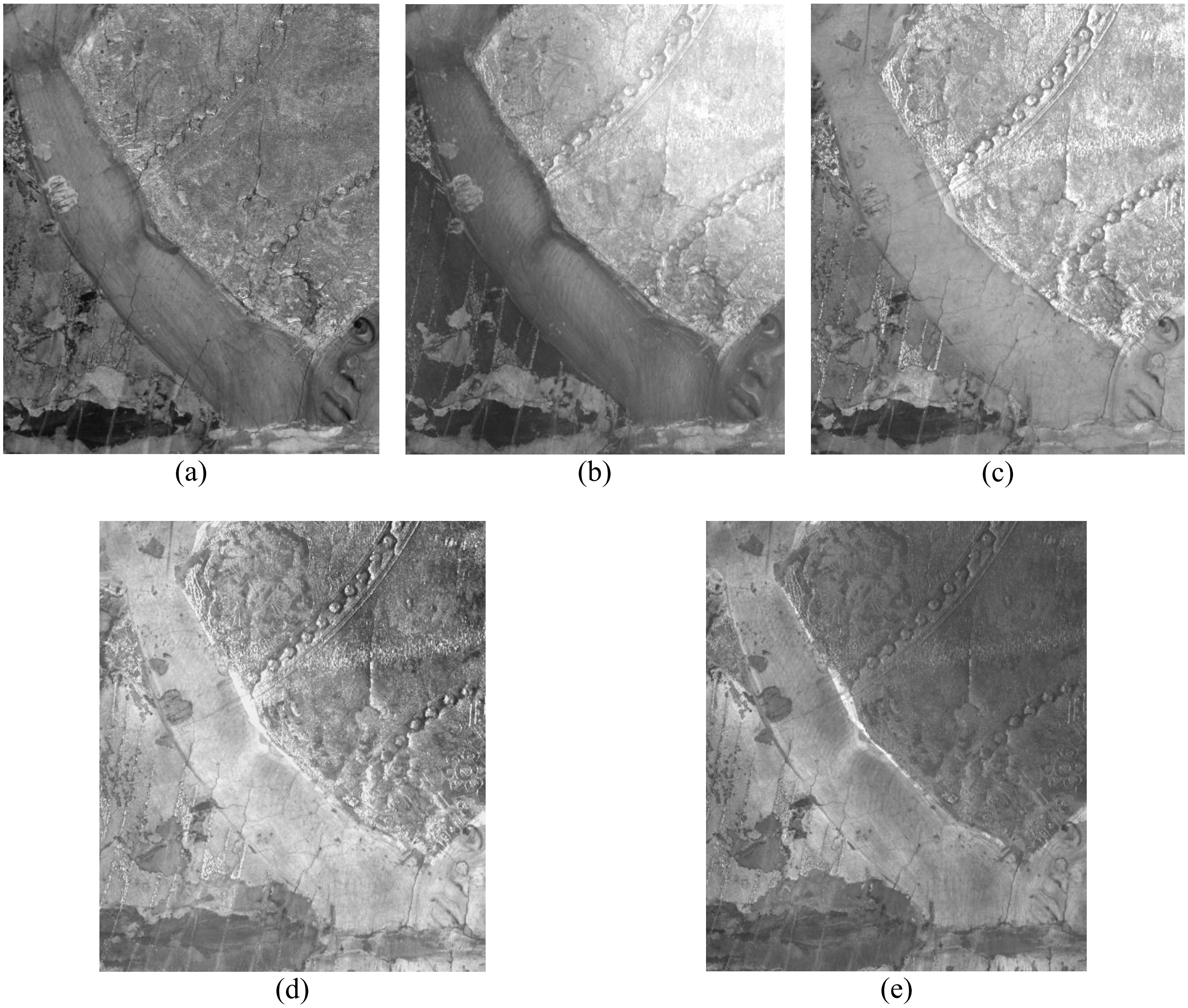


Fig. 9. Virgin with Child (Cimabue), detail of the Child's arm. a) Reflectogram obtained with the IR; b) CH2 image @850 nm; c) CH14 image @2265 nm; d) CH14-CH2 and e) CH14/CH2

A comparison between the reflectogram obtained with the old INOA scanner and the score image T1 (see Fig. 12) shows that this latter contains nearly all the information of the former.

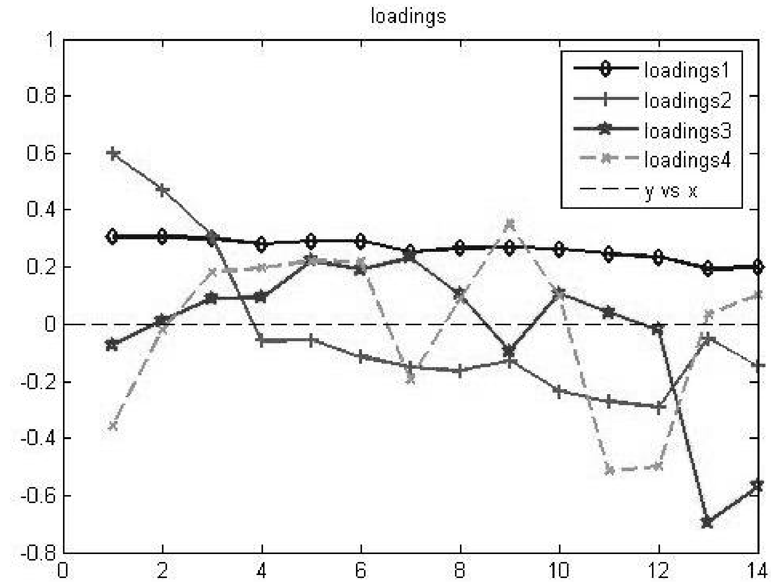
On the basis of this similarity, and in order to enhance the information missed in the reflectogram, we put together the score images T2, T3 and T4 ascribing them to the R, G, and B channels respectively, to obtain a "false-color" score-image. Similarly, the standard false-color image[20], obtained ascribing the IR, R and G images to the R, G, and B channels respectively, was done and the two false-color images are shown in figure 14c and d. In the false-color image obtained from the score images, many details of the under-drawing that are present in the reflectogram and then in the score image T1 are missed, but other details come out strongly. For instance, at both sides of the Virgin's neck two retouches, resembling a sort of earrings, are clearly visible in the false-color score-image, that are completely invisible both in the reflectogram (Fig. 12a) and in the standard false-color image. The same happens for the sleeve cuff of the Virgin's vest, for the vest under the Child's right leg and for the Virgin's mantle on the painting left. Probably all of them have suffered a restoration intervention. The armchair has a little square that appears as differently colored in both the false-color images but was not visible in the reflectogram. Finally, the background, that looks uniformly colored in the standard false-color image, seems to be different in the two halves of the painting in the false-color score-image.

The last example of application is a panel painting by Maestro di Barbavara (end of XIV – beginning of XV century), that is part of the Poldi-Pezzoli collection and is owned by a museum in North Carolina. The panel (Fig. 14e and f) is painted on both the front (San Gaudenzio) and the rear side (coat of arms). The restores of the Opificio delle Pietre Dure, where the painting is presently under repair, maintain that on the painting verso the superposition of two coats of arms are present, belonging to two different families that probably owed the painting in subsequent periods. The multi-spectral analysis was devoted to the determination of the underlying coat of arm.

Figure 13 shows the reflectogram and the CH13 image @1930 nm: the wing is much more visible in CH 13 image than in the reflectogram due to the higher transparency to the NIR radiation in this spectral band of the blue color that covers the underlying coat of arms.


(a) (b) (c)

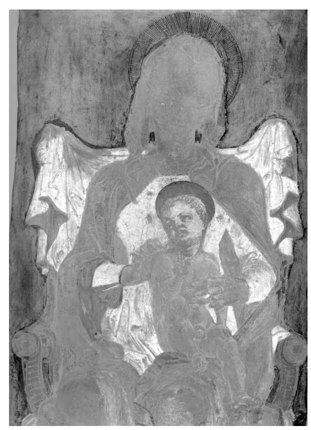
Fig. 10**.** Virgin with Child (Cimabue), detail of the Virgin bust. a) Reflectogram obtained with the IR; b) CH14/CH2; c) CH10/CH3



(a)

(b)

(c)



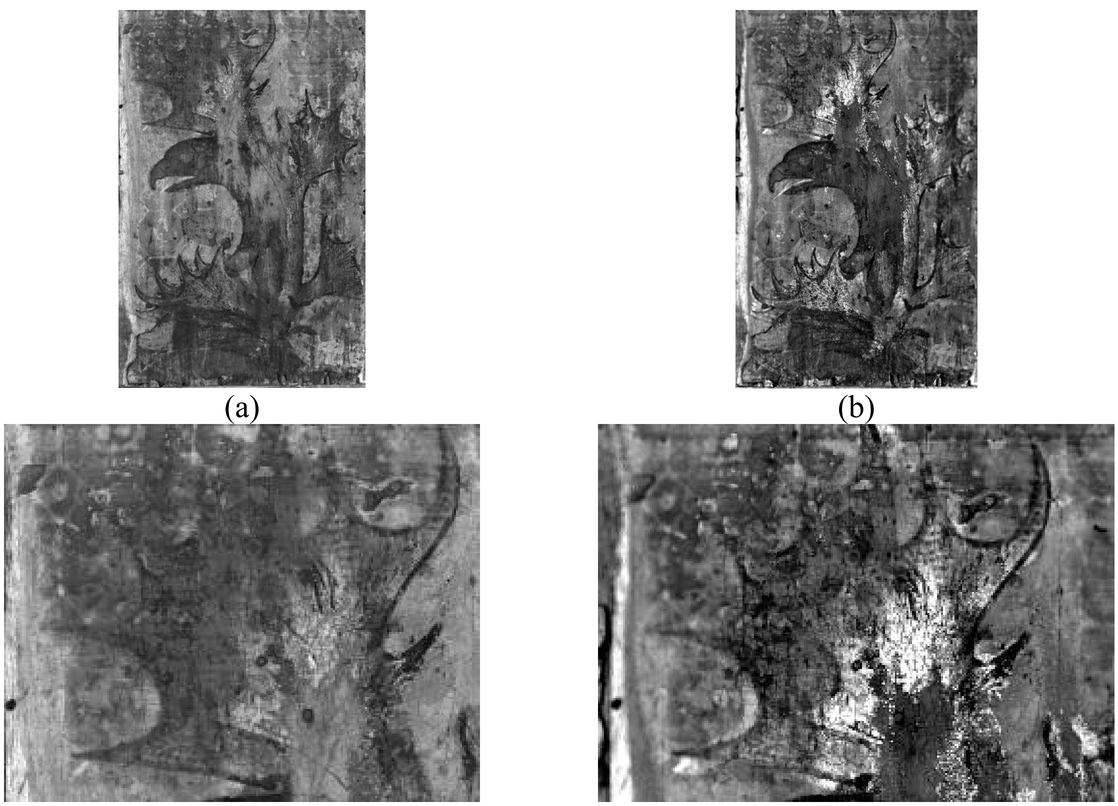
(d)

(e)

Fig. 11. a) Plot of the loadings vs the wavelengths. Score images b) T1 resuming the 91.9% of information; c) T2 resuming the 5.5% of information; d) T3 resuming the 1.9% of information; e) T4 resuming the 0.3% of information.

(a) (b)

Fig. 12. Cosmè Tura, Virgin with Child: a) reflectogram and b) score image T1.



(a) (b)

(c) (d)

Fig. 13. Maestro di Barbavara: a) reflectogram and b) CH13 @1930 nm of the painting verso. c) and d): detail of the wing in the reflectogram and CH13 image, respectively.

4. CONCLUSIONS

In this work we have presented a scanning device for multi-spectral IR reflectography, based on contact-less and single-point measurement of the reflectance of painted surfaces in the spectral band ranging from 800 to 2300 nm. The instrument acquires the radiation back-scattered from a painting surface in 14 spectral bands, with a FWHM bandwidth of 50-100 nm. The simultaneous motion of the lighting system and the collecting optics limits surface heating and, together with point-by-point surface sampling, assures uniform lighting. Moreover, single point detection entails off-axis -aberration free images. Thus, even if in the acquisition phase our scanner is probably time-consuming compared with most of existing devices, the time loss is regained because data do not need neither geometrical nor intensity corrections, and thanks to hardware registration the 14 monochromatic images are automatically superimposed.

Extending the spectral sensitivity beyond 1.7 μm, that is the cut-off wavelength of the *old* INOA scanner, seems to add interesting information about the painting status. A few examples of applications were then presented, as well as a very first data handling. Pixel-by-pixel difference and ratio images were calculated to enhance the presence of retouches and re-paintings. A statistical analysis was also carried out in order to make automatic the research of hidden details. Principal Component Analysis (PCA) was computed on a panel painting dated XV century, resulting in an enhancement of details that are not visible in the reflectogram obtained with the *old* INOA scanner. PCA seems to be the right way to detect any dishomogeneity in the painting surface: the standardization of the procedure, by means of easy-to-use software also for non-specialized people, is an important goal for making multi-spectral reflectography accessible to restorers and conservators.

As the main drawback of our system is heaviness, a new mechanics will be designed. The realization of a new bundle is also planned so to make the procedure repeatable. We are studying a method for producing bundles with fibers aligned within a 3 micron error. The key point will be the use of custom mechanical masks for the fiber alignment, together with aluminum and plastic small rods to keep the fibers at the right distance. An auto-focus system is at present under development, that will keep the surface of the painting focused during the scan, thus allowing the acquisition even in case of irregular surfaces, and will simultaneously provide a measurement of the surface shape.

Fig. 14. (a) RGB image of Cimabue. Cosmè Tura: (b) RGB image; (c) false-color score-image and (d) false-color image. Maestro di Barbavara: picture of the (e) recto and (f) verso.

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