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Remote and contactless infrared imaging techniques for stratigraphical investigations in paintings on canvas

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Abstract

In the analysis of complex stratigraphical structures like painted artefact, infrared (IR) techniques can provide precious information about elements hidden under superficial layers of the artwork, such as pictorial features and structural defects. This paper presents a novel complementary use of reflectographic and thermographic techniques for the survey of three baroque paintings, preserved at the Chigi Palace in Ariccia (Italy). First, the IR-ITR laser scanner prototype has been used for the preliminary and remote near-IR reflectographic survey of the areas where the canvas was located. The resulting map was then used for planning the thermographic and mid-IR reflectographic studies, focusing the analyses on the most interesting areas of one of the paintings, called "La Primavera". The combination of the three imaging techniques revealed several details not visible by the naked eye, such as restored lacunas and pentimenti, demonstrating the validity and complementarity of the proposed combined methodologies.

1 Introduction

In the past, information on historical paintings concerning their realization procedures by the artists, as well as their preservation conditions, were gathered mainly from literary and historical sources. Starting from the XX century, the use of scientific methodologies has become a common worldwide practice and extensively applied to the study of cultural heritage (CH). Thus, the so-called Heritage Science provides the possibility of comprehensive and in-depth investigations of the artworks. Stratigraphical analyses are particularly useful on paintings where several layers overlap, from the support and the preparatory layers up to the paint and varnish levels [1]. As typical underlying features, the underdrawings and the *pentimenti* can be considered as the most interesting ones from the artistic point of view: the former can be defined as the sketch of the final painting drawn by the artist directly on the preparatory layer beneath the painted layer; the latter can be described as any change applied by the artist during the painting of the artwork. In such a complex context, the possibility of investigating through the layers without an invasive approach became an important goal of Heritage Science, aimed also at the analysis of the *modus operandi* of the artist. Among the non-destructive diagnostic and documentation methods [2–10], the imaging techniques make it possible to carry out a complete non-contact analysis of painted artefacts by exploiting the interactions between the artwork materials and the different types of employed radiations. In particular, Infrared (IR) imaging can inspect some of the subsurface layers thanks to the transparency of most of the pictorial materials to the IR radiation, which can thus also reach the preparatory layer, where underdrawings are normally found. Furthermore, the intensive technological progress occurred over the last decades has led to the development of more affordable, easy to use and less invasive systems, specifically designed for such kind of applications. In Infrared Reflectography, several new approaches have been recently introduced, enabling to achieve advanced results in the field of CH by the use of solid-state sensors [11–13] and innovative scanning systems [14–17]. Even though they can ensure high-resolution imaging of the observed features, these types of systems are generally close-range methodologies, providing the best performances with small/medium

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size objects and/or requiring the placing of the artworks as close as possible to the acquisition apparatus, a practice that is not always possible. Another close-range technique is Infrared Thermography, recently employed as a non-destructive method in several fields, such as testing and evaluations in different kind of objects [18–20], investigation of the thermal transport properties of different materials [21–25] and specific applications on library and documentary artworks [26].

In this study, three different IR imaging methodologies have been selected for the non-destructive investigation on oil-on-canvas artefacts with the aim of understanding the employed artistic techniques and of characterizing the performed restorations of some painted artworks preserved at the Chigi Palace in Ariccia (Italy) [27]. Here, many important baroque artworks are preserved, such as the painting series called *Le Quattro Stagioni* (“the Four Seasons”) executed by Mario Nuzzi in cooperation with other important artists working in Rome in the Baroque period. The four paintings of the series, which have never been investigated before, have the peculiarity of having been created by two different artists, each canvas with different artistic techniques so that the investigation of subsurface features became fundamental for the understanding of their realization process. The approach used in this work was to combine prototypal and consolidated techniques for both remote and close-range inspections of the three canvas placed in the dining room of the Palace. A preliminary reflectographic survey was carried out in the NIR range (1.55 µm) by means of a laser scanner prototype[1] (Infrared-Imaging Topological Radar: IR-ITR), used to remotely inspect the artworks still hung up on the walls which hosted them. Then, the results of the survey were used to direct the analyses in the MWIR range (3–5 mµ) by the use of pulsed thermography (PT) and and Reflectography (MIR) for a closer and in-depth investigation of the most interesting areas of the paintings, identified by the scanner, after they were taken down from the walls. The NIR reflectographic scan was possible thanks to the IR-ITR system capability to work remotely even at large distances and wide angles from just one acquisition station [28], while the thermographic and MWIR reflectographic analyses provided further elements concerning the inner layers of the paintings [29, 30]. The additional analysis confirmed most of the details captured by the laser scanner and also highlighted further pictorial details and restored defects of the canvas.

This work proposes a novel and non-destructive approach for the investigation of elements buried inside the multilayer structure of paintings, carried out over large areas without compromising the resolution and the image quality necessary for revealing even relatively small features.

Fig. 1 Mario Nuzzi and Filippo Lauri, La Primavera, 1658–59, oil-on-canvas, 145 × 220 cm, Palazzo Chigi, Ariccia (Italy)

2 Materials and methods

2.1 The painting

The study is focused on an oil-on-canvas called *La Primavera*, one of the four paintings composing the series of *Le Quattro Stagioni* that symbolizes the main phases of human life (the youth, the maturity, the decline and old age). The four paintings were made between 1658 and 1659 by Mario Nuzzi in collaboration with some of the most important painters of central Italy. The series was commissioned by Flavio Chigi, nephew of Pope Alessandro VII, and it is today preserved inside one of the main baroque residences in Italy, the Chigi Palace in Ariccia (Rome, Italy) [31–33]. In all the paintings, Mario Nuzzi, also known as Mario de’ Fiori,[2] painted the floral parts of the canvas, while the human figures representing the allegories were painted by the other artists, a different one for each artwork. In the case of *La Primavera* (Fig. 1), the human characters were depicted by Filippo Lauri [34], who accomplished in this painting his first large work. Unlike Mario Nuzzi, who painted the floral ornaments almost impulsively also on a big canvas, Filippo Lauri usually made smaller artworks after accurate preparatory studies.

The main character of this painting is *Flora*, a young woman representing the Youth, surrounded by six cherubs preparing decorations with several kinds of flowers. The woman is depicted wearing classical clothing and a crown

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[1] The IR-IRT system has been developed in the ENEA Research Centre of Frascati (Italy).

[2] The name was due to his exceptional skill in depicting flowers (*Fiori* means “flowers” in Italian).

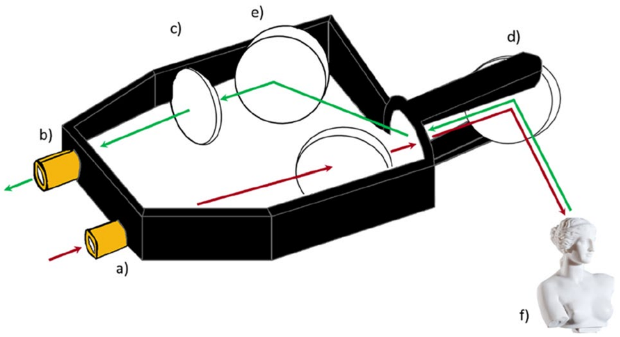

Fig. 2 The IR-ITR optical head setup: the red line represents the laser path, while the green beam is the back-reflected light from the target. **a** laser source input; **b** back-reflected signal output; **c** focal lenses; **d** motorized mirror; **e** mirrors; **f** target

composed by roses, lying on a marble basement and showing a rose as a trophy. The spring allegory and her hand gesture were often represented in the artistic production of Filippo Lauri [35], more often on copper supports, but in this painting, the author showed his great versatility and artistic skills. Despite the two different painters' hands, the figurative and floral parts of this artwork are deeply connected in a perfect harmonisation [36].

The four paintings are hung on the dining room's walls of the Palace, 2 m above the floor and they have all the same dimensions (145 × 220 cm).

2.2 Infrared imaging techniques

The first technique employed in this study was the NIR IR-ITR laser scanner, which has been used to inspect three of the four paintings, with no scaffolding being employed. Secondly, MWIR thermographic and reflectographic analyses have been performed on *La Primavera,* focusing attention on the most interesting areas identified by the scanning survey.

2.2.1 IR-ITR laser scanner

The IR-ITR system is a laser scanner prototype entirely developed at the ENEA Research Centre of Frascati (Rome, Italy), employed for remote inspections of sub-surface features in layered objects, such as painted artworks [37].

The scanner is assembled in two distinct parts: an optical head, composed of lenses and mirrors for focussing, steering, and collecting both the incident laser beam and the back-reflected light; the electronic module, for the opto-electronic signals conversion and vectorization, the data acquisition and storage. The two modules are interconnected by a monomodal fibre, from where the laser beam is emitted, and a multimodal fibre, used for collecting the back-reflected signals from the target. As shown in Fig. 2, the optical head includes an aspheric lens (not visible in the scheme because it is positioned very close to the laser input (a)) for focusing the launching laser beam on the artwork surface and a doublet lens (c), 50 mm in diameter and 150 mm in focal length, for the detection of the reflected light from a distance of up to 10 m. The laser spot has a diameter of about 2 mm and it is swept onto the target through a double-motorized mirror (d) operated by a positioning system, which permits a TV-raster-like movement of the beam on a surface (f) positioned frontally with respect to the scanner.

This system is based on the amplitude modulation (AM) technique of the infrared laser source [38, 39]. The AM technique combined with the lock-in detection, which can detect weak signals also in a noisy environment, estimates simultaneously the amplitude and the phase-shift of the signals generated by the light reflected from the target. Such a method allows the remote probing of different types of surfaces like the painted ones, revealing features buried beneath a few microns of the painted layer. The amplitude information, dependent on the laser/matter interaction characteristics at a specific optical wavelength, contributes to the grey-level intensity reconstruction of the target, while the phase-shift information can be used to estimate the distance between the scanner and the investigated surface. At present, the system is equipped with a monochromatic laser source in the NIR range ($\lambda = 1.55$ µm with a power density of less than 1 mW/mm^2). The reflected signals are detected by a low-noise photodiode detector and its amplitude and phase are measured by the lock-in amplifier unit. Due to mechanical limitations of the optical head, the rotation movement of the scanning mirror is $80^\circ \times 310^\circ$, with a maximum point-to-point precision of 0.002°, with a total resolution for a single complete acquisition of 40,000 × 155,000 pixels (6.2 GPixel). This system is able to work independently from the surrounding lighting conditions, scanning the surfaces even during the night.

The acquisition procedure and the post-processing are controlled by custom software developed in the MATLAB environment, namely ScanSystem and itrAnalyzer. The first software sets the scanning parameters based on the working requirements (area, resolutions, timing and more) and runs the acquisition; the second one is composed of several image processing algorithms to improve the mapping quality, whose results can then be exported in the most common file formats. A scheme of the IR-ITR system acquisition workflow is reported in Fig. 3

To assess the resolution of the IR-ITR scanner, the easiest way is to compare it to standard camera resolution, even though the two types of systems are not homogeneously comparable because of the different technology on which they are based on.

The total angle of view of a camera equipped with a Full-Frame CCD and a group of lenses with a 200 mm focal length is about 12°. The same angle

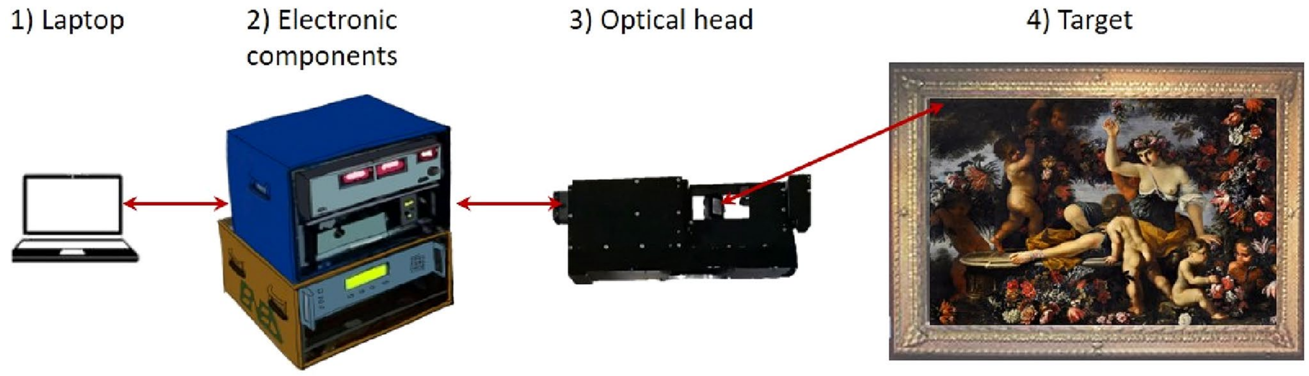

Fig. 3 A scheme of the IR-ITR workflow: (1) the PC for the control of the digitalization processes; (2)the electronic module, composed by the laser source,the acquisition device and the motion controller; (3) the optical head, for steering the laser beam onto the target (4) and for collecting the back-reflected light

of view can be captured by the IR-ITR scanner with a pixel resolution of 36 MPixel estimated according to: $\left[(12^\circ/0.002^\circ)\mathrm{x}(12^\circ/0.002^\circ)\right] = 6000 \times 6000$ pixels.

A comparison between a projective system, like the camera, and a 1:1 system, like the IR-ITR system, can be done comparing the printable area at a 300 dpi (or ppi in the case of the scanner) of the two instruments. The maximum printable support length with a 300ppi (pixels-per-inch) resolution is given by the following formula:

$$\text{length} = 6000\text{pixels}/300\ \text{ppi} = 20'' \ (\cong 51\ \text{cm}) \tag{1}$$

In the case of the IR-ITR scanner, the arc length at 5 m distance, with the same angle of 12°, made by the beam and projected on a hypothetical plane placed perpendicularly in front of the scanner is:

$$\begin{aligned} \text{length}_{\text{IR}\ -ITR} &= 2 \cdot d_{\text{plane}} \cdot tg\left(\frac{\vartheta}{2}\right) = 2 \cdot 5 \cdot \text{tg}\frac{12^\circ}{12} \\ &= 1.06\ \text{m} \quad (= 41.73'') \end{aligned} \tag{2}$$

Comparing Eqs. 1 and 2, it is possible to obtain the IR-ITR scanner resolution (R) at 5 m:

$$R_{\text{IR}-\text{ITR}} = \frac{\text{pixels}}{\text{length}} = \frac{6000\ \text{pixels}}{41.73''} \cong 144\ \text{ppi} \tag{3}$$

Thus, Eq. (1) shows the maximum printable length of the image collected by the camera, while Eq. (2) the maximum length of the surface that can be scanned by the IR-ITR system at 5 m distance (it is capable to digitalize scenes with a 1:1 ratio). Printing the resulting IR-ITR image on the same printable support used for the camera with a length of 20″, the scanner resolution would be close to the requested 300 dpi, making the IR-ITR scanner equivalent to a digital camera equipped with a tele-photo (large ppi) and wide-angle (80° × 310°) lenses group at the same time.

It may be then concluded that the large resolution and the wide-angle of view of the IR-ITR system makes it suitable for preliminary and remote investigations of large objects and scenes, thus enabling the detection of hidden details even at a large distance [40].

2.2.2 Pulsed thermography and MWIR reflectography

Pulsed thermography (PT) has become a widely employed method for non-destructive investigations of artworks, providing information on defects, inhomogeneities, and subsurface features in different types of artworks, such as bronzes [41, 42], illuminations [43, 44], paintings on different kinds of support [45–47]. PT relies on the moderate sample heating produced by the absorption of VIS light pulses and on the subsequent time-resolved measurement of the IR radiation locally emitted from the sample surface. The IR detection is carried out by means of an IR camera which provides a sequence of images, in the following referred to as thermograms, each corresponding to a different delay time with respect to the onset of the pulsed heating. In optically opaque samples, the temperature rise is initially generated at the sample surface and, thereafter, it progressively diffuses over time into the sample volume. The eventual presence of subsurface inhomogeneities, such as those due to defects like delaminations or voids, leads to corresponding modifications in the heat diffusion rate and, consequently, to a time-dependence of the temperature rise at the sample surface areas above the defects different with respect to that above sound parts of the sample. Therefore, the recorded thermograms show time-varying contrast whose analysis may enable the quantitative evaluation of the detected subsurface defects. In particular, such an analysis enables one to discriminate between defects located at different depths into the sample since the contrast typically achieves its maximum

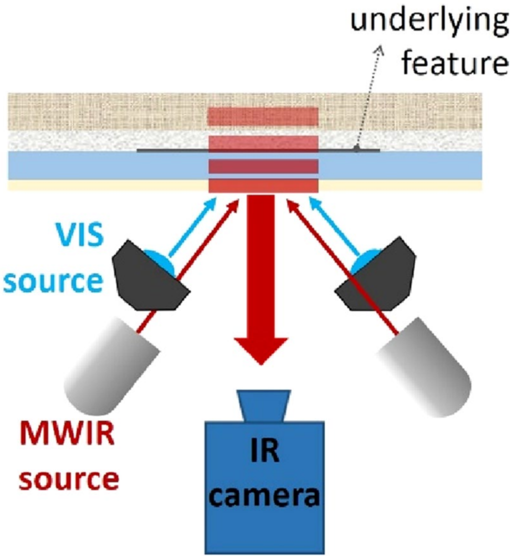

Fig. 4 Sketch of the MWIR experimental configurations using the same detection device (IR camera) and different illumination sources: VIS for the thermographic analysis and MWIR for the reflectographic one

at a delay time value progressively increasing with the depth of the corresponding subsurface feature. Unlike optically opaque samples, in optically semi-transparent ones, such as the ones investigated in the present study, both the VIS light absorption and the IR emission do not exclusively occur at the sample surface but take place also over the sample volume. Therefore, besides the thermal inhomogeneities mentioned before, the thermogram contrast may also originate from subsurface features [48] characterized by different VIS absorption or IR emission properties with respect to those of the surrounding areas. As shown later on, such a circumstance provides a valuable tool for the detection of buried graphical elements such as underdrawings [49].

In the PT setup adopted in the present study (see Fig. 4), the thermal stimulus is induced by the absorption of the VIS light beams provided by two flash lamps (Bowens Estime 3000, maximum power 650 W), employed to produce approximately 2 ms long light pulses. The lamps were positioned at a distance of 0.5 m and with their axes at 45° with respect to the painting surface. The thermographic sequences have been recorded by a Cedip JADE camera[3] for 1 s in full-frame mode with a frame rate of 150 Hz.

Infrared Reflectography is a well-established technique in the field of painting inspection that is especially suited for the detection of underdrawings and/or *pentimenti* laying on the substrate. Such a technique basically consists in the recording of the reflected component of the NIR radiation illuminating the sample. In fact, thanks to the transparency of the paint layers in the NIR range, the incident radiation can reach the ground level where it can be either back-reflected by the support or absorbed by the possibly present drawings, thus giving rise to contrasted features in the recorded reflectographic images. More recently, MIR has been also introduced for CH investigations [50] with the aim of detecting features complementary to those of the NIR reflectography. In fact, MWIR radiation is characterized by a larger penetration depth in comparison with the NIR one and, in addition, pigments typically show different optical absorption and scattering properties with respect to the ones in the NIR range. Owing to this reason, MIR may enable the detection of elements of different compositions and located at greater depth within the artefact in comparison to those detected by the NIR reflectography.

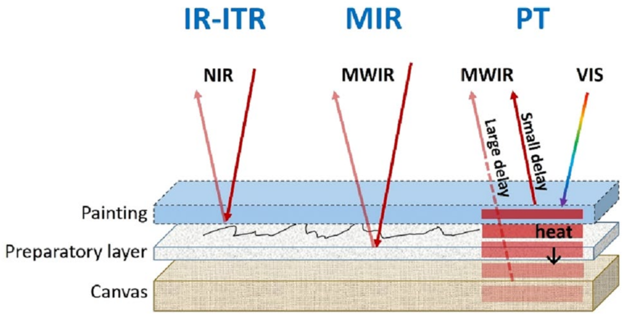

Fig. 5 Schematic representation of the typical stratigraphy of a painting on canvas and the expected depths probed by the (1) NIR scanner (IR-ITR), (2) MWIR reflectography (MIR) and (3) thermography (PT), respectively

As schematically shown in Fig. 4, in the MWIR reflectographic setup the sample illumination has been carried out by means of carbon filament IR sources, positioned at about 1 m from the painting and whose radiation was directed at 45° incidence angle, characterized by an emission wavelength range which includes the spectral range of sensitivity of the employed IR camera. Special care was taken to minimize the exposure time (~ 0.1 s) and the power of the incident IR radiation (< 100 W) to reduce the sample heating and, consequently, the mid-wave IR radiation thermally emitted by the sample. Under such circumstances, the temperature distribution over the painting may be assumed almost uniform and, consequently, the image contrast is mainly originated from local differences in the MWIR optical reflectivity. The same camera and software used for the thermography have been used also for the MIR investigations, thus ensuring the exact pixel-by-pixel correspondence of the images of the same areas recorded by the two techniques.

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[3] Focal Plane Array (FPA) of 320×240 pixel, InSb focal plane array, 30 µm pitch, Noise Equivalent Temperature Difference(NETD) < 25mK at 30 °C.

Fig. 6 IR-ITR image showing the three canvas preserved inside the dining room of the Chigi Palace

When comparing the two techniques, as shown in Fig. 5, PT has been proved to be able to investigate subsurface features over a greater depth with the respect to MIR, which also cannot easily supply information about the depth of the detected inhomogeneities [29]. On the other hand, MIR provides a larger sensitivity to the detection of features characterised by different optical properties in the MWIR range.

The resolution of MWIR images is dependent on the IR camera and on its distance from the target. In this study, MWIR images have been typically recorded with the IR camera positioned at 50 cm from the sample surface, thus corresponding approximately to a 30 × 30 cm (12 × 12″) surface area. Therefore, the resolution (R) can be calculated by the following expression:

$$R_{MWIR} = \frac{\text{number of pixels}}{\text{frame linear size}} = \frac{320 \text{ pixels}}{12''} = 27 \text{ ppi} \qquad (4)$$

It is worth noting that the thermograms can be rendered in grey-scale or false colours. To make the comparison with the reflectographic images more effective, the thermograms shown in this work are presented with a grey palette according to which the hotter areas appear darker.

It should be pointed out that in the combined multi-imaging approach, the usefulness of the specific information that each technique can provide largely depends on the capability to refer the revealed elements to a specific depth. This is not always trivial when applied to multi-layered semi-transparent materials, such as those of the paintings, where optical and thermal processes are involved in the generation of reflectograms and thermograms. In fact, the determination of the absolute depths of the detected subsurface features requires the evaluation of parameters such as the VIS and IR light absorption, the materials emissivity coefficients, and thermal diffusivity. This is very difficult in stratified structures such as those found in paintings, unlike the case of more homogeneous semi-transparent artefacts, such as the paper-based ones [49]. Nevertheless, it will be shown that the time evolution analysis of the thermograms sequence in the case of paintings, combined with the reflectographic results, can provide information on the relative depth of the detected subsurface elements and reveal their eventual different nature.

2.2.3 Acquisition workflow

To keep the room hosting the paintings accessible to visitors, the acquisition workflow developed for this work was organized in the following two steps. First, the IR-ITR system has been used for remotely scanning part of the dining room without moving the paintings. The laser scanner was placed at a fixed position with the distance between the system and the wall/paintings ranging from 3 and 5 m. The data acquisition has been carried out in about 7 h, working during the night after the closing time of the Palace. Then, after having taken down the painting *La Primavera*, MWIR thermographic and reflectographic analyses have been carried out in the specific areas of the painting where the laser scanner data had shown particularly interesting results.

3 Results and discussion

In this section, the results of the above-described techniques are presented and discussed.

As mentioned above, the IR-ITR scanner was used for investigating remotely an area of 15 × 2.5 m^2, Fig. 6 showing the resulting raw data matrix collected by the scanner. The grey levels composing the image are proportional to the intensities of the back-reflected laser light from the target. The grey levels are not representative only of a specific pigment, because the intensity values are affected also by the quadratic effect of the distances: this is the reason why the two paintings on the right appear darker than the one visible in front of the figure. The quadratic effect can be taken into account by a calibration procedure that in the present study

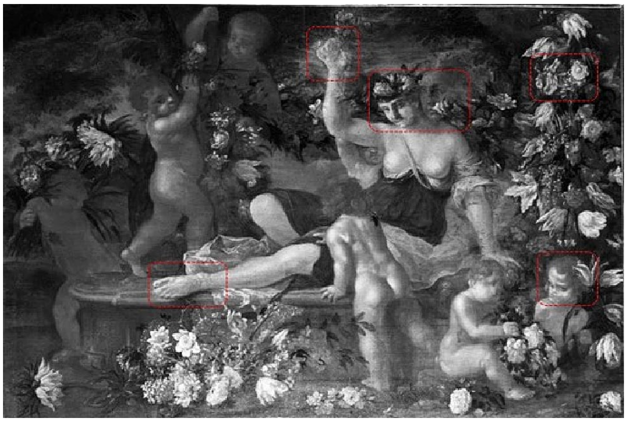


Fig. 7 Detail of the greyscale map of the studied painting obtained by IR-ITR laser scanner. The rectangles indicate the areas of greatest interest which have been investigated with MWIR techniques

has not been performed due to the inaccuracy of the distance measurements obtained by modulating the IR beam at low frequency (300 Hz) [51].

A visual analysis of the entire grey level map has been carried out on three of the "Four Seasons" paintings identifying La Primavera as the most interesting canvas to further investigate. In this respect, many variations with respect to the visible aspect of the artwork have been detected in this painting, marked by rectangles in Fig. 7. Such variations identified with the IR-ITR laser scanner consisted in *pentimenti* and adjustments in correspondence of some parts of the human figures and in the floral details, which have been subsequently analysed by the MWIR techniques.

One of the main features detected by the IR survey is the pentimento in Flora's face (Fig. 8a). As can be clearly observed, the IR-ITR image (Fig. 8b) displayed an additional face adjacent to that of Flora (see the arrows in the figure), possibly referring to a second character appearing in the scene no longer visible in the final version of the painting. Such a face is also partially detectable in the thermogram obtained at early delay times (20 ms, Fig. 8c), while it is not present in the thermogram obtained at longer delay times (300 ms, Fig. 8d), displaying the structural pattern of the canvas, nor in the MWIR reflectogram (Fig. 8e). This is consistent with the additional face originating from the shallow layers below the superficial paint, since both the longer delay time thermogram and the MWIR reflectogram, probe layers located deeper than those probed in the previous two cases. Also connected to such peculiarities of the mentioned techniques is the fact that, only in Fig. 8d, e, it is possible to detect some additional structural features (see arrows), presumably located deeper in the artwork, like those associated with repaired defects in the preparatory layer or in the painting support. The results reported thus far, therefore, point out the usefulness of the combined analytic approach employing multiple imaging techniques.

In this respect, interesting elements have been revealed also in the analysis of the cherub's face shown in Fig. 9. It is seen that both the IR-ITR and MWIR reflectographic images (Fig. 9b, d respectively) are able to reveal several elements situated below the surface paint layer, such as the hair shape and what looks like a change in the face orientation. On the other hand, the thermogram obtained at a small delay (Fig. 9c) is only able to reveal the portrayed surface elements, such as the hair and some flower parts, but with a greater definition/contrast with respect to the original picture. This occurs thanks to the thermal contrast contributing, together with the optical one, to the thermographic image generation.

Similar interesting results are shown in Fig. 10, which refers to Flora's right hand. The IR-ITR image (Fig. 10b) shows a different hand silhouette, with respect to the visible picture, and also a change in the ring finger position. This may reflect particular attention by the artist to the hand pose because of the central role attributed to the gesture of *Flora* showing the rose as a trophy. The thermogram (Fig. 10c) and the MWIR reflectogram (Fig. 10d), in addition to the pictorial sub surface features, also detect several repairs in all the area of the woman's hand, presumably performed during the latest restoration (arrows). This additional detection is possible because thermography is sensitive also to the thermal properties of the studied area, different for the repairs with respect to the sound areas, and the MWIR reflectography is able to probe deeper than that performed in the NIR range and detects the different optical properties of the repairs with respect to the sound parts.

Additional elements can be gathered from the analysis of the IR images obtained in correspondence of *Flora's* left foot, displayed in Fig. 11. In particular, in the IR-ITR image (Fig. 11b) an additional element (arrow) appears below the foot, not visible in the picture in Fig. 11a. Once again, the thermogram (Fig. 11c) is able to show the portrayed elements with a better definition/contrast with respect to the original picture, including the additional element referred to in Fig. 11b. Finally, the MWIR reflectogram (Fig. 11d) provides two important additional information: the different original profile of the foot (arrow) and of the sandal lace profile (rectangle) beneath the bow (shown in Fig. 11a) that was presumably added at a later time. The latter evidence could indicate that Filippo Lauri painted first the entire structure of the human figures and later on added further minor details such as the bow. It should also be pointed out that the differences in the foot profile and the sandal lace are also detectable in the reflectogram in Fig. 11b, but less distinctly than in Fig. 11d, consistently with the fact that the MWIR reflectography can probe deeper than that performed in the NIR range.

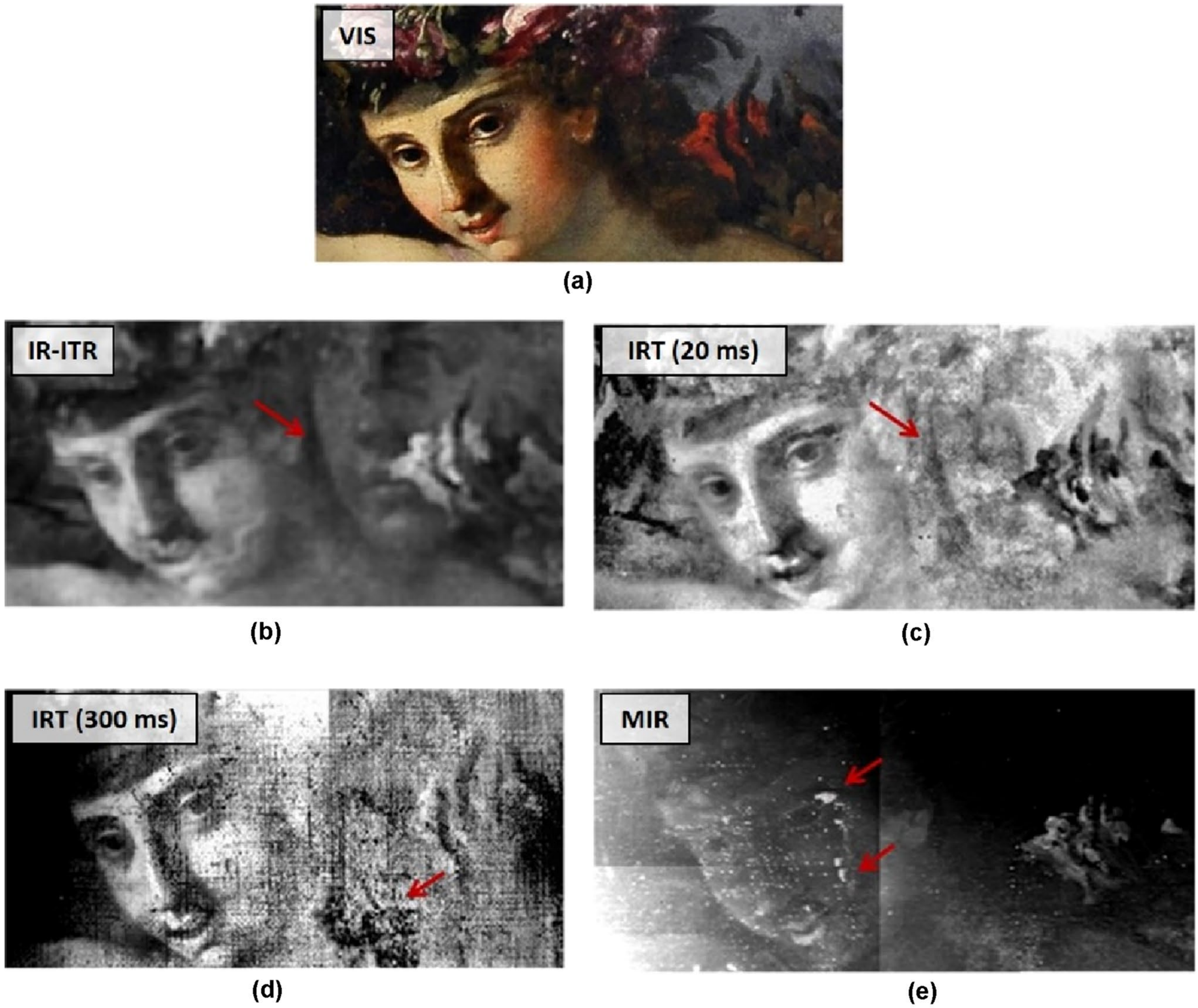


Fig. 8 Flora's face: **a** Picture; **b** IR-ITR image revealing an additional face with the respect to the visible image; **c** corresponding thermogram acquired with 20 ms delay where the second Flora profile is barely detectable; **d** the thermogram acquired at larger delay (300 ms) revealing the structural pattern of the canvas; **e** MWIR reflectogram showing possible repaired defects in the preparatory layer and/or in the support

Some details of the flowers have also been analysed by the IR imaging such as those displayed in Fig. 12. Here all the infrared images disclose an additional structure (see arrows) in the flower on the left not visible in the picture in Fig. 12a. This element may indicate a change of mind of the artist who over-painted the feature with the dark background, perhaps because of the above-mentioned creative impromptu of Mario Nuzzi, who usually painted without a well-defined preparatory drawing. Both the IR-ITR image (Fig. 12b) and the thermogram (Fig. 12c), show also an additional flower (see the rectangle in the figures) barely visible in the picture perhaps because of the darkening of the superficial varnish in that area. It is confirmed also in the present case that the thermographic image is able to display the portrayed elements with a greater richness of details than any of the other displayed imaging.

The reported results thus confirm the usefulness of the multi-technique imaging approach used in this work for the study of a multilayer structure of the painted artwork, adopting spectral ranges that can provide complementary information about the relative depth position of several detected subsurface elements.

The preliminary results of a study for the generation of super-resolution images obtained by the superimposition of those obtained by the three proposed techniques are shown in Fig. 13, with a false-colour display (Fig. 13a) and the resulting

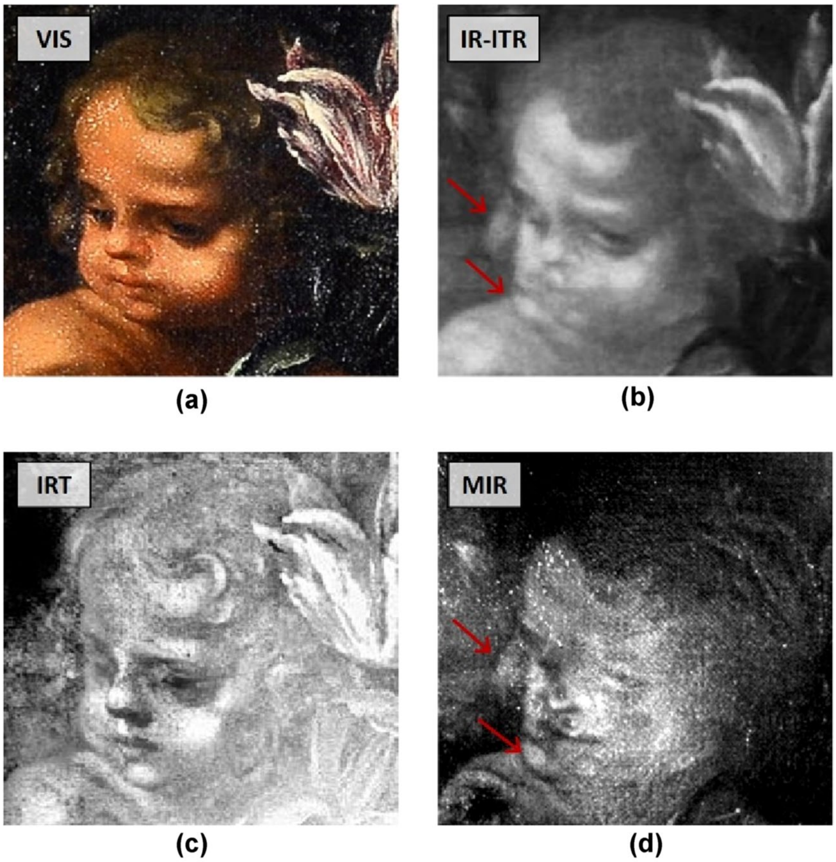
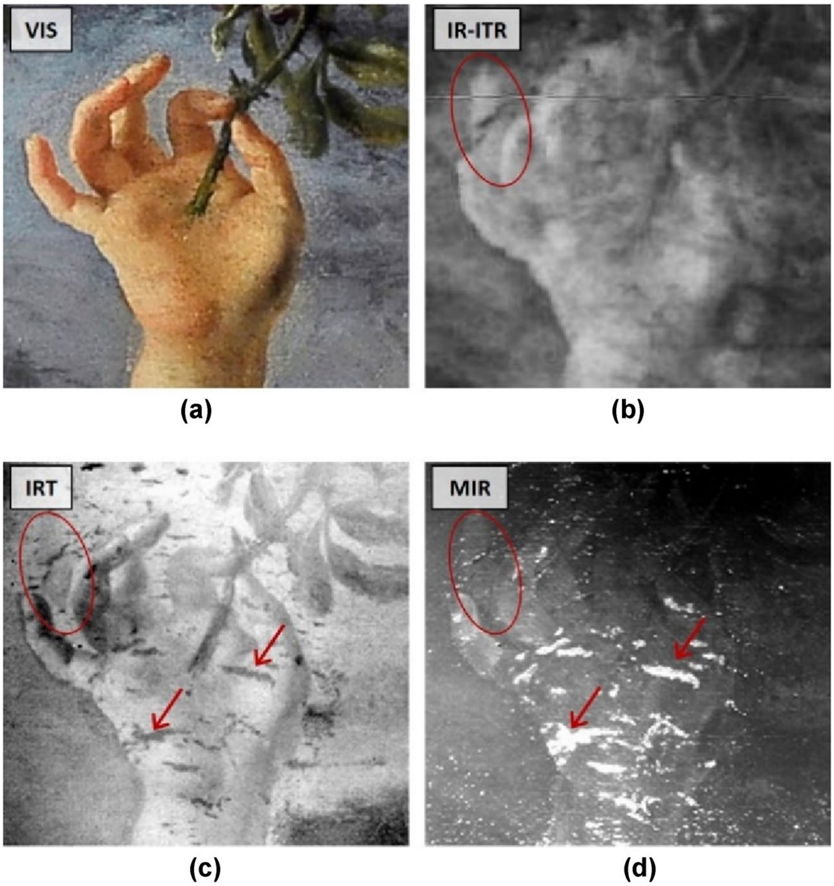


Fig. 9 Cherub's face: **a** Picture; **b** the laser scanner image showing the hair profile and some adjustments of the face; **c** the thermogram allowing to better appreciate the contrast of the face and the flowers; **d** the reflectogram disclosing the same adjustments seen in **b**

data fusion (Fig. 13b). The contribution of each technique employed in this study is clearly appreciable by the different colour of the displayed details in the case of Flora's hand in Fig. 13a: the red area is mainly associated with the PT image that makes the profile of the fingers clearly visible; the green area highlights the main results of the MIR reflectography, showing the restoration of several *lacunas,* and, finally, the blue area can be referred to the IR-ITR image that better reveals the *pentimento* in the position of the fingers. Finally, Fig. 13b shows the same result as Fig. 13a of the data fusion process of the three techniques. Such an image should be considered a preliminary result addressing further research in the processing of super-resolution near- middle-infrared images, which may allow the simultaneous visualization of hidden features in paintings.

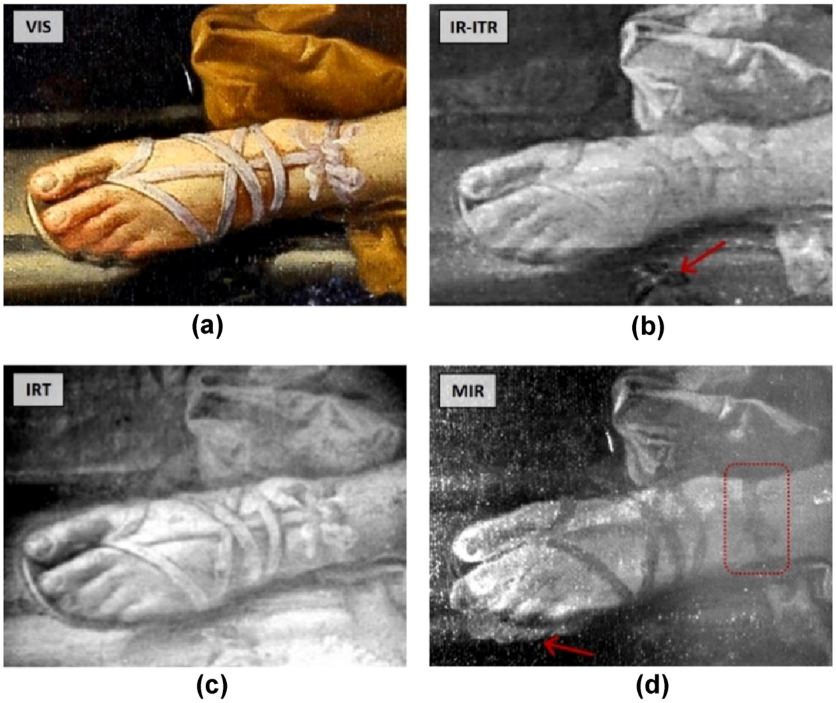
4 Conclusions

In the case of the *La Primavera* painting, useful and interesting results have been obtained by the novel multi-imaging approach combining three different infrared imaging techniques. By means of both the NIR laser scanner and the MWIR camera, reflectographic and thermographic non-destructive analyses have been carried out on a painting, never investigated before, preserved at the important baroque residence of Palazzo Chigi in Ariccia (Italy). This artwork was made by two different artists, making very interesting the description of their employed artistic techniques analysed by the stratigraphic characterization of the painting. The results have highlighted the presence of several *pentimenti,* mainly in correspondence of the human figures, such as in the case of *Flora*'s face, hand and foot, while minor changes of mind and adjustments have been detected in the floral parts. The different elements detected by the three imaging techniques confirm the distinctive *modus operandi* of the two painters: on the one hand, Filippo Lauri had a pre-set approach as demonstrated by the presence of underdrawings and *pentimenti*; on the other hand, the approach followed by the flower master Mario Nuzzi was more extemporaneous. In this respect, the absence of underdrawings could probably be due to the lesser iconographic importance of the floral background compared to the human figures. Moreover, the



(a) (b) (c) (d)

Fig. 10 Flora's right hand: **a** Picture; **b** IR-ITR image revealing differences in the hand profile and in the position of the ring finger (circle); **c** the thermogram disclosing several restored gaps (arrows) and the different finger profile (circle); **d** the MWIR reflectogram highlighting the previous version of the finger (circle) and the several restored gaps (arrows)



(a) (b) (c) (d)

Fig. 11 Flora's foot: **a** Picture; **b** the IR-ITR image allowing to better visualize the herbal detail under the foot (arrow); **c** the thermogram showing the better contrast of the details; **d** the reflectogram revealing a pentimento of the foot profile (arrow) and the absence of the bow (rectangle)

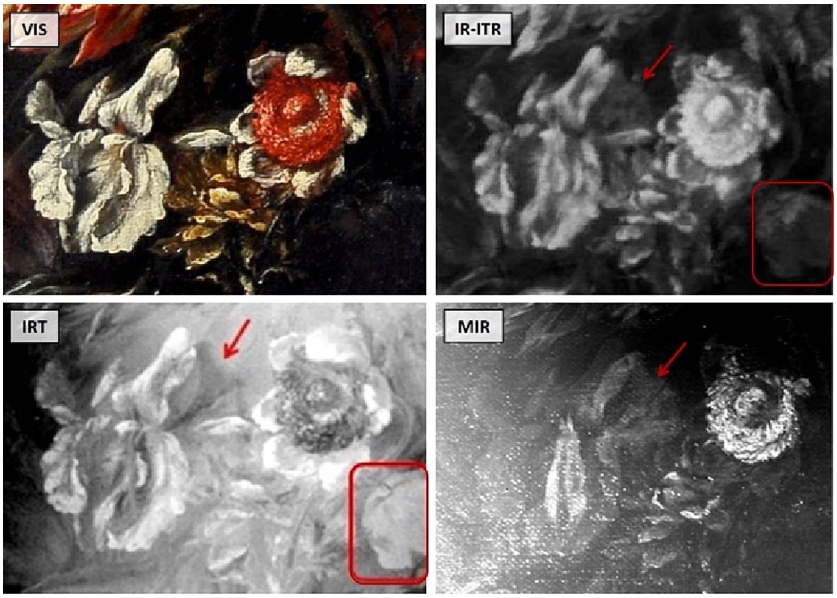


Fig. 12 Flowers: **a** Picture; **b** the IR-ITR image revealing the presence of a hidden petal (arrow) and a further floral element (rectangle), elements highlighted also by the thermogram (**c**) and the reflectogram (**d**)

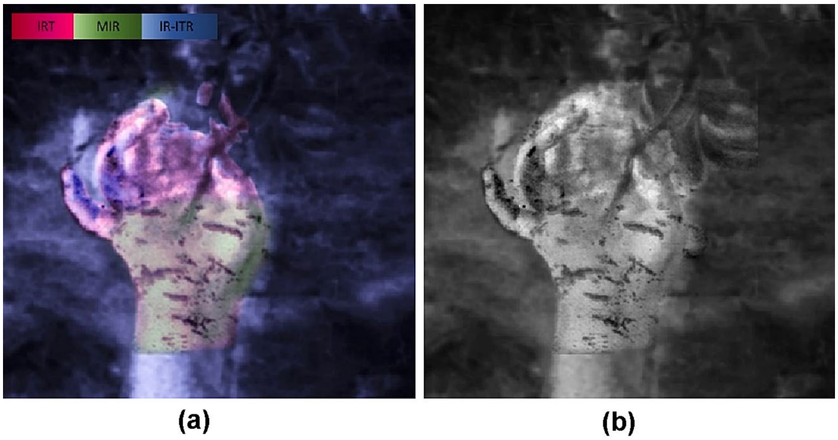


Fig. 13 Flora's hand. **a** the false colours show a super-imposition of the three imaging techniques results: red is the IRT, green is MIR and blue is IR-ITR; **b** data fusion in a super-resolution image

structure of the canvas is well-preserved in general even if several restored gaps have been identified in several areas of the painting.

Even if some of the technologies here described are not mature for the research market and the outcomes are still at an early stage, the results obtained in this work are very promising and the novel workflow presented opens a new scenario for the combination of different infrared systems for high-resolution, remote and close-range inspections of painted artefact. Finally, an example of post-processing integration of the images provided by each of the used methods has been presented. The preliminary results of images post-elaboration provided challenging results in the data fusion which will be included in the future perspective of the presented work as a valuable tool for the investigation of paintings.

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Declarations

Conflict of interest The authors declare no conflicts of interest.

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