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From surface to subsurface: Integrating imaging techniques and laser profilometry in artworks study

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ABSTRACT
This study aims to present the results obtained from the profilometric and reflectographic analyses of the painting on panel *L'Ebbrezza di Noè*, attributed to Antonio Bazzi (known as *Il Sodoma*), preserved at the Galleria Nazionale di Arte Antica in Palazzo Barberini (Rome, Italy). Utilizing an advanced integrated scanning system, we employed a high-resolution laser profilometer with a 405 nm laser line, a lateral resolution of 12.5 µm and a height resolution of 1.6 µm, along with a SWIR uncooled camera equipped with an InGaAs detector with a resolution of 320 × 256 pixels, operating within a spectral range from 900 to 1700 nm, to scan and analyze the artwork. By selecting significant details, we highlighted the potential of a multi-instrument approach in accurately interpreting the complex information revealed through diagnostic imaging of artworks. Specifically, profilometric images were compared with infrared and false-color images to determine whether hidden features beneath the paint layers can be detected through surface topography.

Section: RESEARCH PAPER

Keywords: profilometry; infrared reflectography; surface analysis; artworks; cultural heritage; conservation science; principal component analysis; multivariate analysis

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1. INTRODUCTION

The study of paintings involves addressing the complexity of their layered structure, where each layer is chemically different and unevenly distributed across the surface. Each layer undergoes various degradation processes over time, depending on its chemical composition [1], [2], [3]. In addition, the artwork undergoes changes induced by human intervention, such as retouching and restorations carried out at different times [4], [5]. All these factors vary for each work of art and contribute to its final appearance. However, simple observation under visible light does not fully reveal the creative and conservative processes that the artwork has undergone. Therefore, it is important to employ various analytical techniques that can provide information from different depths of the painting, possibly in a non-destructive, non-invasive way, to preserve the integrity of the artwork. Combining imaging techniques such as infrared reflectography and laser profilometry can offer valuable insights into both the subsurface and surface morphology of paintings.

Infrared reflectography is one of the most widely used techniques for studying paintings, as it provides information about the layers beneath the surface [6], [7]. Infrared radiation can penetrate the paint layers to the ground layer, revealing details that are not visible to the naked eye, such as preparatory drawings, any changes made by the artist, and other aspects related to the execution technique [8]–[12]. Additionally, thanks to the variable transparency of materials in the infrared spectrum, infrared and false-color images can provide partial qualitative information about the materials employed [13], [14].

Laser profilometry [15]–[17] has been applied in recent decades in the field of cultural heritage for both 3D surface digitization and precise monitoring of relevant morphological features [18], [19]. Using a 3D topographic map of a painting surface, it is possible to document the state of conservation of the artwork (e.g., by measuring micro-deformations in the paint layer and monitoring the movement of the support) and provide information on the execution technique, revealing traces left by tools such as brushstrokes, incisions, and scratches. Furthermore, the data obtained allow for the measurement of surface roughness [20], [21].

Both profilometry and reflectography can be easily applied in situ, which is particularly important for large or immovable artworks. The suitability of these techniques is notably due to their non-invasive and non-destructive approach to the surface being examined, requiring no contact [22], [23]. Both analyses provide a digital image of the artwork that contains additional information beyond what is visible to the naked eye. Reflectographic infrared images and profilometric images offer complementary information: while reflectography explores what lies beneath the paint surface, laser profilometry provides a precise mapping of the surface itself.

The inherent heterogeneity of artworks, both in terms of composition and creation processes, as well as conservation history, often complicates the interpretation of the acquired data, as it can be difficult to discern the original aspects of the artwork and differentiate between original and restored sections. For this reason, statistical analysis can be useful for more accurately interpreting the collected data [24]–[26], such as Principal Component Analysis (PCA) used in this study. PCA allows the reduction of complex datasets while retaining the most relevant variance, thus facilitating the identification of correlations, distinctions between original and restored areas, and material differences that may not be easily detectable through a simple visual inspection. This reduction can operate even on heterogeneous data coming from different techniques, enabling the extraction of all the information collected, including the fine interactions among the analytical observables that could be undetected through a separate treatment.

In this study, we applied a multi-technique approach combining infrared reflectography and laser profilometry with PCA-based statistical analysis to investigate a specific case: the painting *L'Ebbrezza di Noè*, housed in the Galleria Nazionale di Arte Antica in Palazzo Barberini (Rome, Italy). The investigations aimed to gather information on the artistic technique used in its execution and the state of conservation of the artwork.

2. MATERIALS AND METHODS

2.1. Painting description

L'Ebbrezza di Noè (Figure 1a) is a painting on panel from the 16th century (ca. 1540–1550), attributed to Giovan Antonio Bazzi, known as *il Sodoma*, and held in the storage facility of Palazzo Barberini [27]–[29]. The panel measures 1700 x 1200 mm, and was originally composed of four horizontal wooden boards glued together, later fixed to a frame with three vertical crosspieces on the occasion of a restoration intervention. This artwork revisits a biblical subject, earlier depicted in the frescoes of the Sistine Chapel: *L'Ebbrezza di Noè* by Michelangelo (1508–1510) [30]. The profilometry and

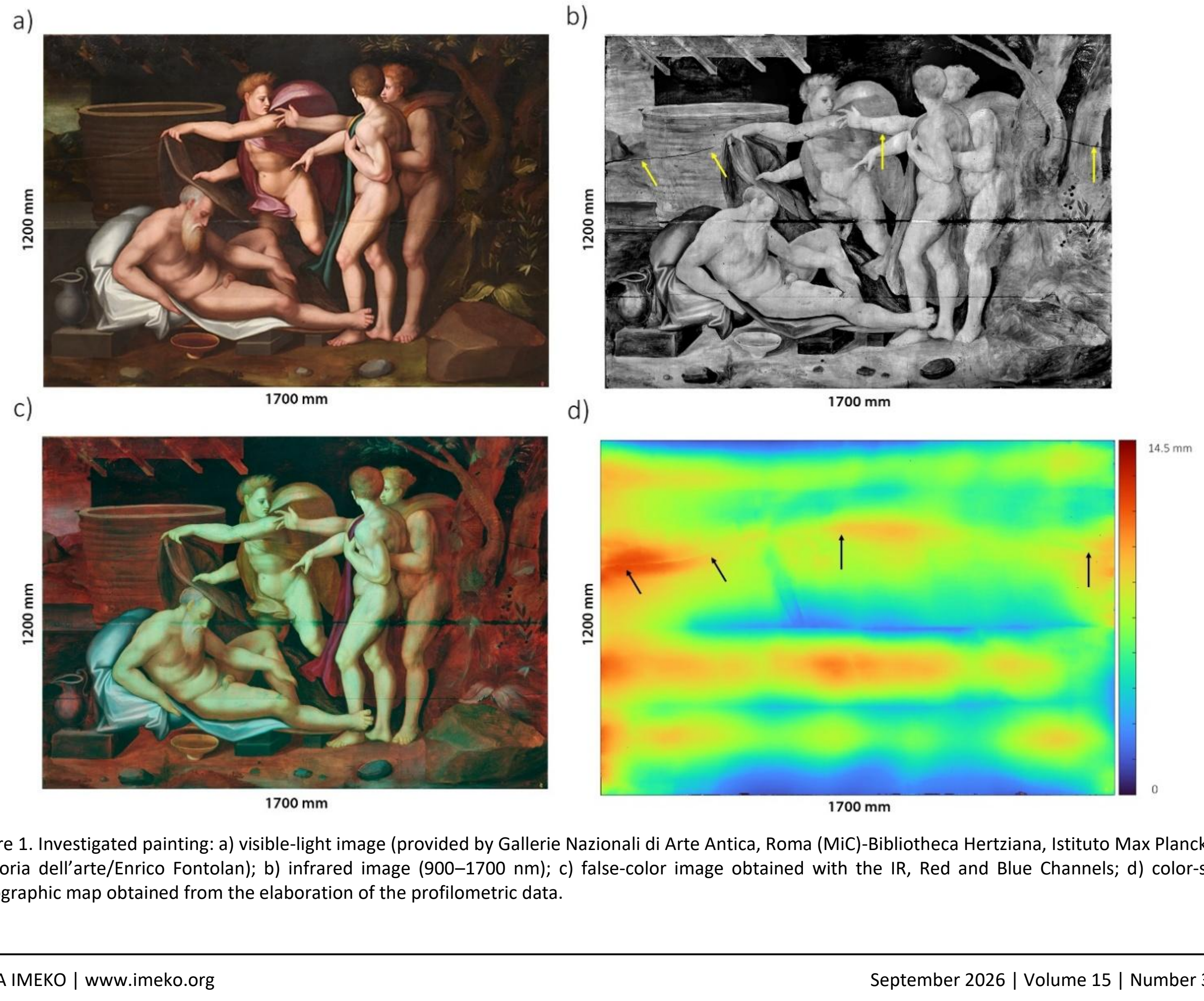

Figure 1. Investigated painting: a) visible-light image (provided by Gallerie Nazionali di Arte Antica, Roma (MiC)-Bibliotheca Hertziana, Istituto Max Planck per la storia dell'arte/Enrico Fontolan); b) infrared image (900–1700 nm); c) false-color image obtained with the IR, Red and Blue Channels; d) color-scale topographic map obtained from the elaboration of the profilometric data.

reflectography measurements were conducted at the Restoration Laboratories of the Museum of Ancient Art in Palazzo Barberini.

The analyses aimed to determine whether *il Sodoma* might have seen Michelangelo's preliminary sketches, and whether he had composed the painting covering Noah's nudity, or if the figure had been intended to be depicted nude from the outset. Additionally, since the artwork at Palazzo Barberini has undergone several restorations, these diagnostic analyses were made to understand the original appearance of the composition and its changes over time.

2.2. The multi-analytical scanning system

The developed scanning system (Figure 2) consists of the following components, described in detail elsewhere [31], [32]:

• Laser profilometer: a high-resolution laser profilometer by Keyence (Controller Model: LJ-X8000A; Head Model: LJ-X8080), with a laser line (λ = 405 nm) measuring 39 mm, a CMOS detector, and a working distance of 72.0 mm ± 20.5 mm. The instrument delivers real-time both luminance and topographic data with a lateral resolution of 12.5 µm and a z-resolution of 1.6 µm [33].

• Infrared camera: the Xenics Bobcat 320 TE0 GigE 400, a SWIR uncooled camera based on an InGaAs detector with a 320 × 256 pixels resolution and a quantum efficiency of 80 %. It operates within a spectral range from 900 to 1700 nm and achieves frame rates up to 400 Hz. The camera is equipped with a 35 mm f/1.4 SWIR lens, and illumination is provided by two halogen lamps. The camera streams live images directly to a PC via a LAN cable, allowing images to be saved directly on the computer without the need for an additional frame grabber [34].

• Motion system: the profilometer and the infrared camera were mounted on two motorized linear axes (positioning resolution ± 0.01 mm) using an adapter, allowing a maximum scanning area of 300 × 300 mm² in the XY plane. Figure 2b insert shows the profilometer and the infrared camera mounted on the X-axis using a shared mechanical adapter.

• Elevating platform: the entire setup has been transferred on a hydraulic lifting trolley, which can be raised up to 1500 mm. The platform has been modified by integrating a system that enables the adjustment of the inclination angle, ensuring optimal scanning conditions.

Although the two devices share the same mechanical scanning stage, each one has its own acquisition protocol, operational speed range, and working distance. As a result, the profilometry and reflectography acquisitions are carried out in separate runs, rather than simultaneously. However, the possibility for these techniques to share the same reproducible high-resolution positioning system represents the key factor to quickly join the information and efficiently find correlations and interactions among data.

2.3. Data acquisition and data handling

The profilometry measurements were performed using a Python-based workflow that integrates the *LJXAwrap* library to interface with the profilometer [35]. 365 profiles measuring 39 mm × 300 mm were acquired in batch modality, with a sampling frequency of 500 Hz. Each profile overlaps by 10 mm with the previous one.

For infrared reflectography, 120 images were captured with the software Xeneth 2.7, from a distance of 1500 mm. Subsequently, close-up details were taken at a distance of 600 mm. Both the infrared images and the topographic maps were stitched using the Open Computer Vision Python Library [36].

The final infrared image (Figure 1b) was then aligned with the visible-light image (Figure 1a, provided by the Gallerie Nazionali di Arte Antica, Roma (MiC)-Bibliotheca Hertziana, Istituto Max Planck per la storia dell'arte/Enrico Fontolan), and a false-color processing was done. Specifically, in the RGB image, the blue channel component was excluded. The infrared monochromatic image was assigned to the R channel, the red image to the G channel, and the green image to the B channel. This process generated a false-color image (Figure 1c) that contains all the information from the constituent monochromatic images, particularly the infrared image.

Some details of the profilometry images were selected and processed under simulated raking light, then manually aligned onto the visible-light images. By adjusting the transparency of the two different layers, both images could be viewed simultaneously, enabling a more comprehensive interpretation of the data.

The subsequent elaboration for visualizing the topographic color scale map of the artwork surface (Figure 1d) was done using MATLAB [37].

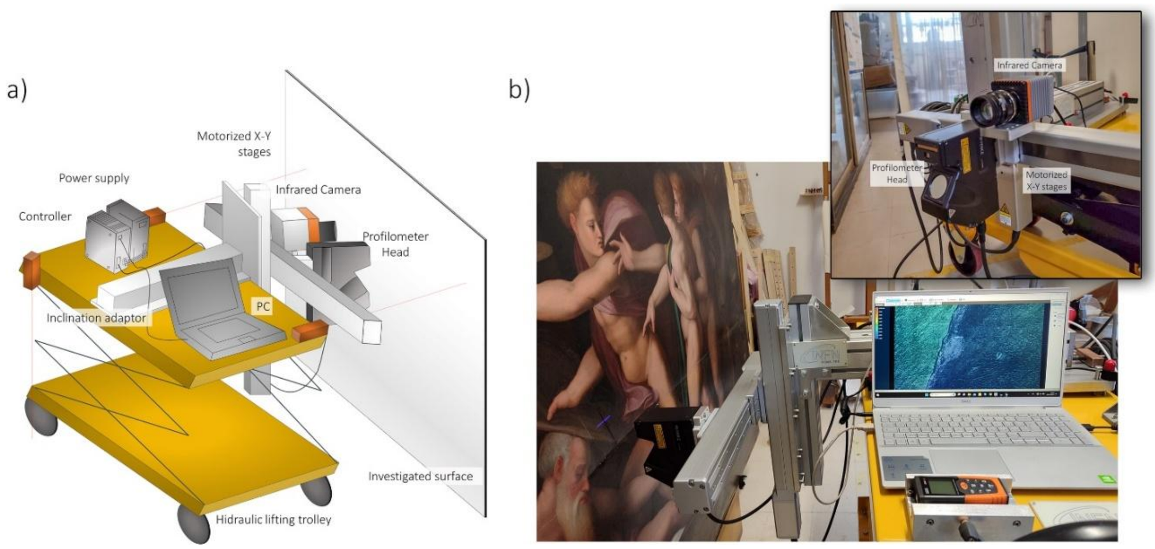

Figure 2. a) schematic representation of the scanning system; b) transportable scanning system during the measurements in Palazzo Barberini.

2.4. Principal Component Analysis

Principal Component Analysis (PCA) is a multivariate statistical method used to simplify the analysis of complex data, especially when there are many correlated variables, making it difficult to identify differences among individuals. PCA, with a preprocessing of the original variables, creates a reduced number of new uncorrelated variables, known as principal components (PCs), which highlight similarities and differences. In Principal Component Analysis, the distance between two data points is measured using the Euclidean distance. Before calculating these distances, the data values are standardized, which means adjusting each variable so that it has a mean of zero and a standard deviation of one. This ensures that all variables contribute equally to the distance, regardless of their original scale. This Euclidean distance plays a crucial role in PCA, as it helps determine the relative differences between data points in the transformed space [38]–[40].

In this study, PCA was applied to a hypercube consisting of infrared, red, green, and blue images using MATLAB, in order to integrate and transform the data from these images, enhancing the clarity and interpretability of the spectral differences. The multispectral images were initially pre-processed with a conversion to double format and grayscale to standardize them and reduce complexity, followed by data centering. Subsequently, the images were combined into a matrix for Principal Component Analysis (PCA), which extracted the first three principal components (PC1, PC2, and PC3). The PC score maps were visualized individually using a colormap, which provides significant information (variance) to differentiate various painted areas based on their different spectral responses. Then, the components were normalized and combined into a single image, allowing the spectral variations to be visualized in a single, new false-color representation. Subsequently, loading plot and score density plots of different pairs of PCs were plotted using a chromatic scale, to identify low-density (blue areas) and high-density (red areas) pixel clusters in this new coordinate system [41]–[43]. From these plots, Regions of Interest (ROIs) were then selected to visualize the pixel distribution in the false-color image.

An attempt was made to perform PCA on the combined visible, infrared, and profilometric data. However, the results were not helpful in the identification of relevant features, and therefore were not considered.

3. RESULTS AND DISCUSSION

The profilometric data were processed to generate a high-resolution topographic map of the painting (Figure 1d), which is represented using a color scale ranging from blue (lowest points, set at 0.0 mm) to red (highest points, set at 14.5 mm). The map provided valuable insights into the deformation of the wooden support. These data are useful for monitoring the wood movements over time and for assessing how the crossbars on the reverse side of the artwork helps mitigate the deformation of the support or, conversely, induce new stresses. The reinforcement is effective on the upper side, but less so in the central area. These deformations have also caused the formation of tension lines, and some cracks have formed (indicated with the arrows in Figure 1b and Figure 1d).

In the infrared reflectography image (Figure 1b), in addition to the cracks indicated by yellow arrows, other areas exhibiting a dark response can be observed. These features are mainly located at the junctions between the wooden panels, and in correspondence with holes left by woodworm activity. The dark infrared response in these areas is indicative of material loss, which was subsequently compensated for with fillings and retouches in order to restore the visual continuity of the pictorial surface.

Infrared reflectography and false-color imaging also provided complementary information on the pictorial layers. No evidence of an underdrawing differing from the final composition was detected in the infrared image. However, several features not visible in the visible-light image (Figure 1a) became apparent in the infrared reflectography image (Figure 1b); these features are discussed in detail later in the text. The false-color image (Figure 1c), on the other hand, proved to be useful to identify additional details, added later in the vegetation on the right, as some leaves and mulberries display a different coloration, suggesting a different composition to the original painting.

To further investigate the painting technique and subsequent alterations, two representative details were selected for closer analysis: a face and a jug (Figure 3 and Figure 4, respectively), as they were considered especially informative. In the face detail, both the profilometric image (Figure 3d) and, partially, the infrared image (Figure 3b) revealed incision marks on the ground layer (yellow arrows). These incisions do not appear to follow an ordered pattern; rather, they are randomly distributed across the painting surface. A first hypothesis is that they may be accidental incisions. A second hypothesis is that these incisions were made to guide the placement of the cartoon on the panel before the transfer of the composition. A third hypothesis is that these incisions were intended to improve the adhesion of the paint layers to the ground layer. The prepared surface may have been too smooth, and these random incisions created an irregular texture that facilitated better anchoring of subsequent paint layers. The composition and degree of surface uniformity of a surface can influence the development of the craquelure [44], [45]. In particular, excessively smooth and homogeneous surfaces may promote or accelerate crack formation over time; the presence of surface incisions disrupts this uniformity, contributing to a redistribution of stresses within the ground layer, and potentially reducing its susceptibility to detachment or fracture.

As previously observed, the wooden structure of the roof, which was later partially covered with darker, materially undefined brushstrokes, becomes totally visible in both the infrared and false-color images. In Figure 3b and Figure 3c, it is possible to observe the fluid, horizontal brushstrokes of the background, beneath which lighter areas are discernible in the infrared image (Figure 3b) and appear reddish in the false-color image (Figure 3c). The false-color shift of these areas beneath the dark background brushstrokes is similar to the color of the wooden roof beam. From these images, it has been hypothesized that beneath the dark background there is a lighter layer of paint, which could either be a brown preparatory ground or an earlier, lighter-painted background (presumably the wooden wall of the hut depicted in the biblical scene).

A detailed comparison of the color scales of the three PCs, carried out on small sections of the painting and focusing on areas where overlaps, overpaintings, and pentimenti are most evident, enabled the reconstruction of the sequence of paint layers through a stratigraphic and recursive approach, maintaining a principle of consistency across the entire image.

Figure 3e and Figure 3f, corresponding to PC1 and PC2 respectively, provide a more comprehensive view of the painting

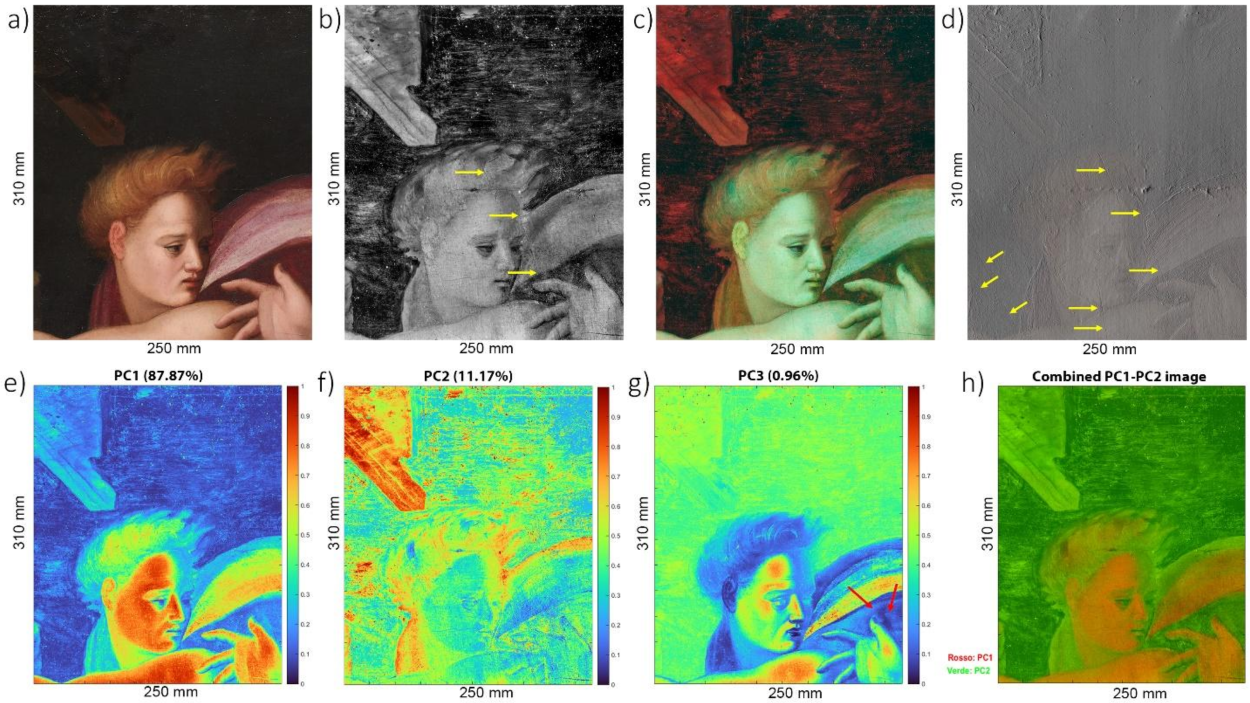

Figure 3. Face detail a): visible light image; b) infrared image (900-1700 nm); c) false-color image; d) profilometric image processed under simulated raking light, overlapped on the visible light image; e) PC1 colormap; f) PC2 colormap; g) PC3 colormap; h) combined image between PC1 and PC2.

stratigraphy. In the PC1 image, red areas are associated with flesh tones, executed at the end of the creative process; in the PC2 image, the red areas correspond to the lower paint layer (which is also detected in the infrared and false-color images). The upper layer has a green shade. The blue areas correspond to subsequent restorations. Merging PC1 and PC2, this sequence is more evident. The red contribution of PC1 highlights the upper layers, corresponding to the final steps of the artistic execution. The brownish details may correspond to the restorations. Finally, in the PC3 image (Figure 3g), a small change in the angle of the thumb can be observed. A dark-blue area (indicated with red arrows) shows the initial placement of the finger, which was then shifted.

A loading plot and a score density plot between PC1 and PC2 were then obtained (Figure 5a and Figure 5b), and several ROIs were selected. In the loading plot (Figure 5a), it is evident that PC1, which accounts for the largest portion of variance (87.87 %), is strongly correlated with the visible channels (R, G, B). The similarity in the orientation and direction of the R, G, and B channel vectors reflects the limited chromatic range of the painting, which is predominantly characterized by brown tonal variations and strong luminance contrasts. Conversely, PC2 (11.13 %) is primarily influenced by the infrared (IR) component. Such clear differentiation between the loadings of the two PCs highlights the complementary contribution of visible and infrared data in differentiating between the lower and upper paint layers. The score density plot (Figure 5b) further illustrates these relationships, showing how the pixel scores get clustered along PC1 and PC2. Three regions (ROI 1–3) were identified based on these clusters, each corresponding to different tonal areas of the painting, following the same approach previously adopted in another case study [24]. In the three areas (Figure 5c, Figure 5d, Figure 5e), it is possible to notice, progressively from ROI 1 to ROI 3, how a sense of depth is achieved through chiaroscuro, starting from the more shaded areas (in ROI 1) to the brighter areas (in ROI 3), in accordance with what was suggested by the R, G, B loadings. In ROI 1, the scores are narrowly distributed, quantitatively indicating a homogeneous stratification from the background to the surface layers; the related red-marked points (Figure 5c) share similar features, and thus it can be hypothesized that the preparation of the background corresponds to a single step in the creative process. This is also consistent with the observation that the beam, appearing dark in visible light, is nonetheless positioned in a distinct area of the density plot, thereby confirming its material differentiation. In ROI 2 and ROI 3, the scores are progressively shifted toward higher PC1 values, corresponding to mid-tones and highlights, respectively. The red-marked pixels in Figure 5d and Figure 5e are scattered across the darker, shaded areas of the face, progressively towards more illuminated ones. In a general view, the progression from ROI 1 to ROI 3 effectively reflects the painter's use of chiaroscuro to create depth.

In the jug detail, both the infrared and false-color images (Figure 4b and Figure 4c, respectively), show areas with different spectral responses, indicating that the object has been repainted, especially around the handle and spout (yellow arrows). The profilometry image (Figure 4d) also shows thick brushstrokes layered over the original ones. The multispectral images, and even more so the PCA images, suggest that the jug has been slightly shifted downwards (the original outline, indicated with a white dashed contour, marks its initial placement, which was later covered). A halo is visible above the handle and at the opening of the jug, particularly in the PC2 image (red halo, Figure 4f) and in Figure 4h, the merging between PC1 and PC2, indicating the probable original position of the object, which was higher up. Additionally, as a result of this movement, the spout appears slightly lengthened (indicated by red arrows in the PC3 image, Figure 4g). Despite these changes, the handle is misaligned with the body of the vase, suggesting that it may have originally been

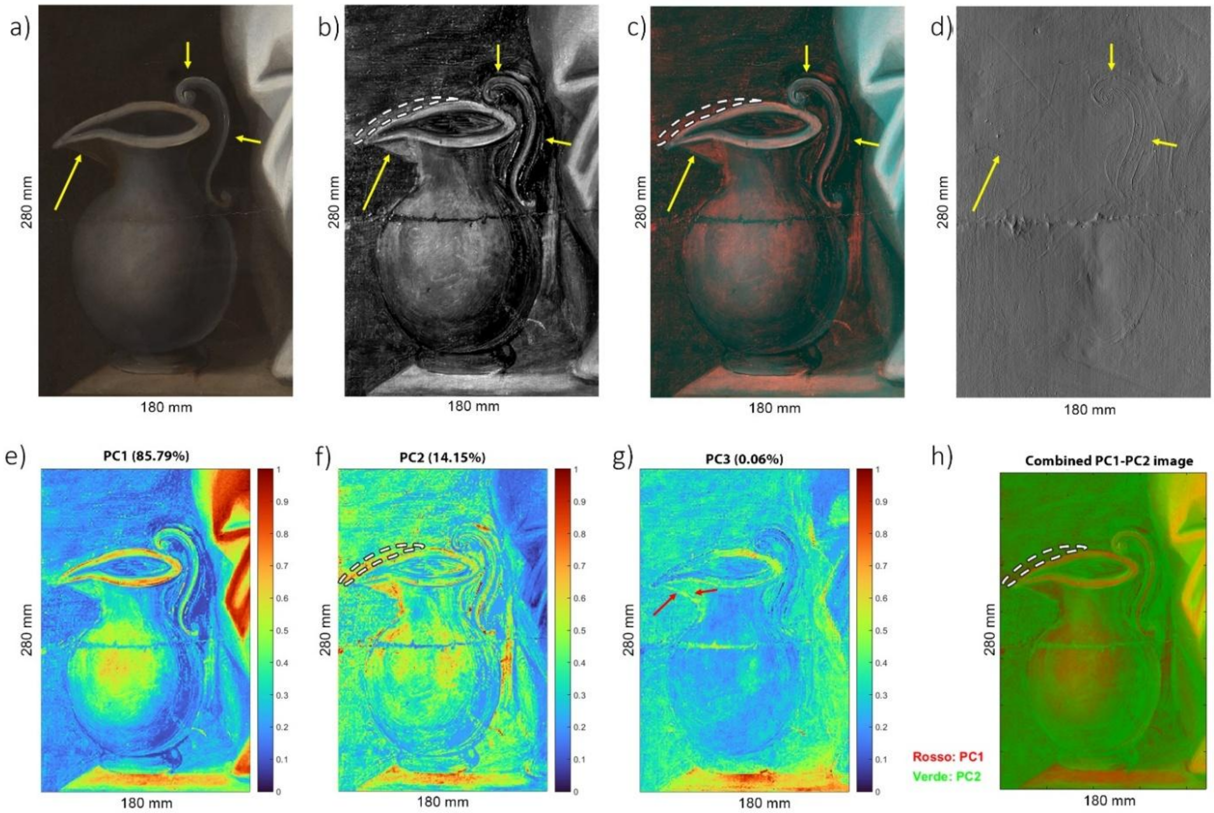

Figure 4. Jug detail a) visible light image; b) infrared image (900-1700 nm); c) false color image; d) height image; e) PC1 colormap; f) PC2 colormap; g) PC3 colormap; h) combined image between PC1 and PC2.

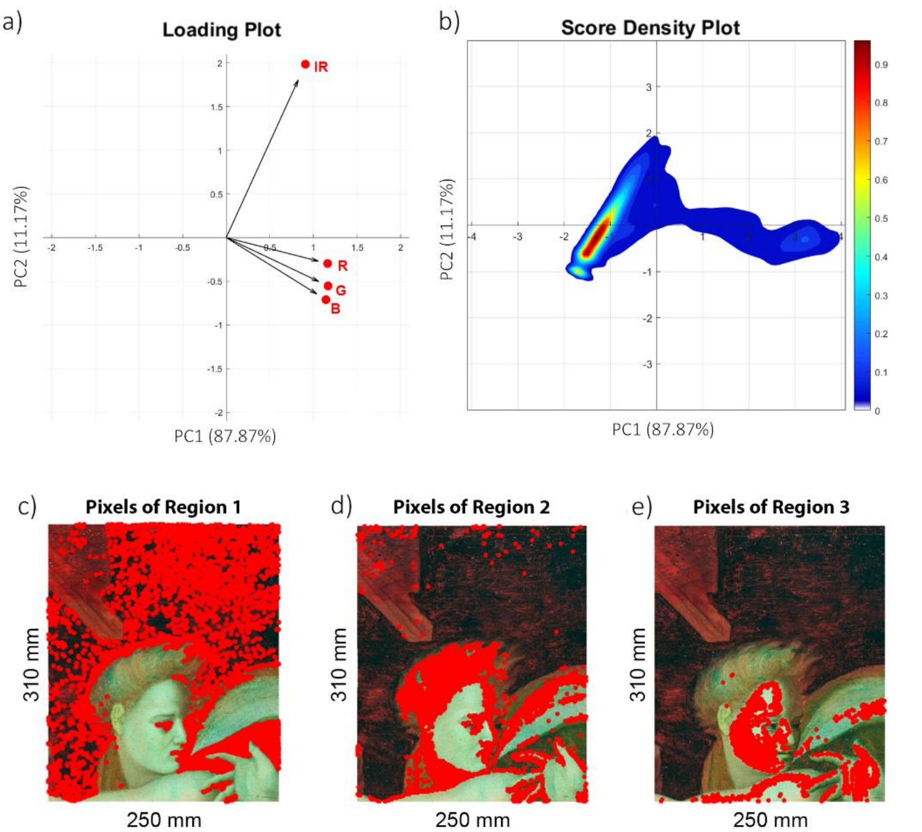

Figure 5. a) loading plot of PC1 vs PC2; b) score density plot of PC1 vs PC2; c) pixel distribution of ROI 1; d) pixel distribution of ROI 2; e) pixel distribution of ROI 3.

in the correct perspective, but was presumably altered during a restoration.

Through the comparison of profilometry, infrared, false-color, and PCA data, it has been possible to reconstruct the main phases of the creative process, in accordance with established practices in seventeenth-century panel painting [46], [47], and to clearly identify how subsequent conservation interventions have altered the painting's current appearance. Such alterations are often perceptible to a trained eye, as they reflect the evolution and degradation of the original materials. However, in certain cases, morphological changes can distort specific details, rendering them aesthetically less pleasing than originally intended, according to the opinion of the restorers responsible for the conservation of the painting. Diagnostic tools such as those employed in this case study are therefore essential, as they help reconstruct the history of the artwork and provide a clearer understanding of its visual and material transformations.

4. CONCLUSIONS

This study demonstrated the potential of an integrated, non-invasive imaging approach that combines laser profilometry, infrared reflectography, and PCA-based multivariate analysis for the investigation of artworks. The proposed multi-instrument methodology emphasizes the complementarity between surface-sensitive and depth-sensitive imaging techniques, providing information on surface morphology, indirect indications of the support deformation, and the presence of possible stratigraphic discontinuities. The integration of the datasets through PCA further enhances the interpretability of the results, supporting the identification of relationships between original paint layers and restorations.

Applied to the panel painting *L'Ebbrezza di Noè*, this approach proved to be useful in outlining a likely chronological sequence of the execution phases and subsequent conservation events. The painting appears to have been executed following a structured pictorial process, starting with the application of a ground layer, followed by the application of incisions and the definition of the figures' contours, the filling of the main color areas, and the completion of the composition through shading, midtones, and final highlights.

During its conservation history, the wooden support underwent deformations and was affected by woodworm activity, resulting in the presence of holes across the surface. Both the structural deformations and the woodworm damage led to localize losses of the pictorial material, which were subsequently addressed through fillings and paint retouches. In addition to these integrations, numerous retouches were also carried out in other areas of the painting, and further changes were later made with thicker brushstrokes.

These results suggest the importance of integrating imaging techniques with compositional analyses to achieve a more comprehensive understanding of the artist's palette, essential for refining hypotheses on the artwork's chronology and provenance.

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