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SfM as Visual Enárgeia of Damage in Paintings

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Abstract

This study explores the use of Structure from Motion (SfM) to analyze and enhance artworks, focusing on *Uomo che legge* (1964) by Renato Guttuso. SfM, a digital photogrammetry technique, is examined for its ability to embody *enárgeia*—a vivid visual clarity—by generating detailed 3D models of cultural heritage objects. The method reveals geometric deformations and material discontinuities, which are crucial for assessing the conservation state of delicate works. Through a structured five-step process, high-resolution data were captured and processed for a non-invasive analysis of structural and material alterations. This method not only aids in restoration efforts but also enhances visual engagement with the artwork, highlighting its historical significance. The study emphasizes SfM as a link between technology and perception, providing a fresh perspective on preserving cultural heritage.

Keywords

SfM, paintings, damage, geometric discontinuities

1. *Introduction*

Digital surveying technologies are increasingly central to Visual Communication, capturing tangible objects of cultural heritage and transforming them into three-dimensional, realistic, and interactive models accessible to a broad audience. These models, available through VR (virtual reality) or AR (augmented reality) devices, embody the concept of *enárgeia* (*ἐναργεία* – clarity or visual vividness), which Philostratus, in his work *On Images* (*Περὶ Ἐικόνων* in Greek), defined as the ekphrastic quality—the capacity of an artwork to render its subject perceptible and vividly alive (Webb, 2016).

Digital surveys, by producing high-resolution models and images, pursue the fundamental goal of all forms of visual communication: making artistic content immediate, accessible, and engaging for a broad audience. Additionally, they fulfil the *enarghetic* objective of educating the public to appreciate art through the lens of visual language, fostering an understanding of the iconographic and symbolic details within paintings (Squire, 2013). When intended for a more specialized audience, these models highlight details and features of artworks that are imperceptible to the naked eye but hold fundamental importance in restoration.

In this context, even the smallest visual element can prove crucial for accurate analysis and preservation of the artwork itself.

This paper delves into the advantages of utilizing three-dimensional digital models to restore paintings, especially those created through photogrammetry. These models highlight essential details and features during the initial analysis phase before restoration begins. Over recent decades, digital photogrammetry has gained traction in various fields requiring non-contact measurements, particularly in restoring architectural, archaeological, sculptural, and pictorial heritage, especially frescoes. Its capability to produce accurate and reality-consistent results, even in confined environments, has been thoroughly documented (Pamart et al., 2017) (Grifoni et al., 2024).

In (Bruno et al., 2022), the reliability of investigations on frescoes is demonstrated through an image-matching process between RGB panoramas acquired by the scanner's integrated camera and single-frame images taken with photographic equipment. However, studies show that digital photogrammetry alone is insufficient and requires integration with other Structure-from-motion (SfM) technologies, especially in frescoes. This aspect is thoroughly discussed in

(Borgogno Mondino, E., 2022), where photogrammetry is combined with polarized portable digital microscopy, fiber optic reflectance spectroscopy (FORS), and X-ray fluorescence spectroscopy (XRF) for the analysis of pigments and their mixtures on the painted surfaces of the 10th-century frescoes in the Byzantine church of Palazzo Simi in Bari. The necessity of combining different technologies is also illustrated in (Max Rahrig et al., 2023), in the analysis of *The Adoration of the Shepherds*, an early Spanish Renaissance wall painting created in 1472 by Paolo de San Leocadio and Francesco Pagano in the Cathedral of Valencia. Aiming to generate a high-resolution photogrammetric image set capable of providing information on preparatory drawings, material differences, damage, painting techniques, and conservation interventions, the study integrated digital photogrammetry with non-invasive multispectral imaging techniques, ranging from ultraviolet (UV) and visible (VIS) to near-infrared (NIR).

All studies emphasize the importance of camera selection and lighting control to ensure the stability and quality of the acquisition system. While there are numerous applications of these methods in the context of paintings such as frescoes, there is still a lack of in-depth literature on the use of digital photogrammetry for movable paintings and even more so for drawings on paper. This article seeks to help fill this gap by analysing a drawing on paper—Uomo che legge (1964) by Renato Guttuso—by experimenting with digital photogrammetry alone.

2. *The case study: Uomo che legge by Renato Guttuso*

"Uomo che legge" is a painting on paper created in 1964 by Renato Guttuso. Currently housed in the Rector's Office at the University of Cassino and

Fig. 1: *"Uomo che legge"* (1964) by Renato Guttuso, frontal view, © Authors, 2025

Southern Lazio, the work belongs to the UNI.Ar.Co. Collection is among the first art acquisitions of the university, which boasts a significant collection of contemporary artworks (fig.1).

This piece belongs to the author's realist period, characterized by a strong figurative sensibility and a careful, critical observation of the contemporary world (Fiaschi, 2004). While a critical analysis of the work is beyond the scope of this study, the focus here is on the material examination of the support and the graphic stroke that defines it. The painting, measuring 1188x1535 mm, is created in black and white using titanium-based pigments, which generate a strong chiaroscuro contrast, enhancing the volumes and giving dynamism to the central subject. The paper appears particularly oxidized by its natural aging process due to oxygen and UV rays.

Fig. 2: Front details: 1| Paper damage; 2| Fabriano paper watermark, © Authors, 2025

The artwork was executed on smooth Fabriano paper, identifiable by the watermark visible on the left side of the front. It was subsequently glued onto a medium-density linen canvas, supported by a walnut-stained fir wooden frame used for the lining. The corner strips, made as a single piece rather than double, contributed to a pronounced unilateral deformation of the paper during the beating process.

The lining and framing were presumably done by the Toninelli Gallery in Milan (Pratesi, 2012), as indicated by the label applied to the recto of the work, which titles it "*Lettore di giornale*" with dimensions of “116x151 cm”. The work has been subject to anthropic damage, a blow causing partial breakage at the bottom during a relocation, and the paper structure appears particularly yellowed (figg. 2-3).

3. *SfM for paintings*

Uomo che legge, as a painting on paper, lacks the materiality and texture of oil on canvas, where thick paint and brushstrokes make degradation or craquelure more visible. Interpreting deformations and quantifying damage are complex but essential for conservative restoration, preserving the artwork's visual impact and authenticity. To address the analysis of artworks like the case of the study, attention has been focused on using the Structure from Motion (SfM) technique, which reconstructs 3D geometry from stereometric frames without direct contact with the delicate artwork (Abate, 2019).

As is well known, the SfM (Structure from Motion) technique, through computer vision algorithms, reconstructs the three-dimensional structure of a scene without prior knowledge of the internal orientation of the camera or the external orientation of the frames. The procedure underlying the most used algorithms—such as the open-source software Meshroom—is divided into three main phases:

1. the automated identification of tie points (key points), i.e., individual pixels in the images and their description through numerical vectors (descriptors).
2. the matching of corresponding (homologous) points detected across different images.
3. Generating a set of correspondences (sparse and dense point clouds).

In paintings, the acquisition is challenging due to homogeneous radiometric and geometric areas, complicating key point matching, especially on unprepared paper like *Uomo che legge*, where yellowing or fading uniformizes the background.

The image quality is crucial and depends on carefully designing the acquisition setup, considering the object's characteristics, image spatiality, and environmental conditions (D’Amelio et al., 2009).

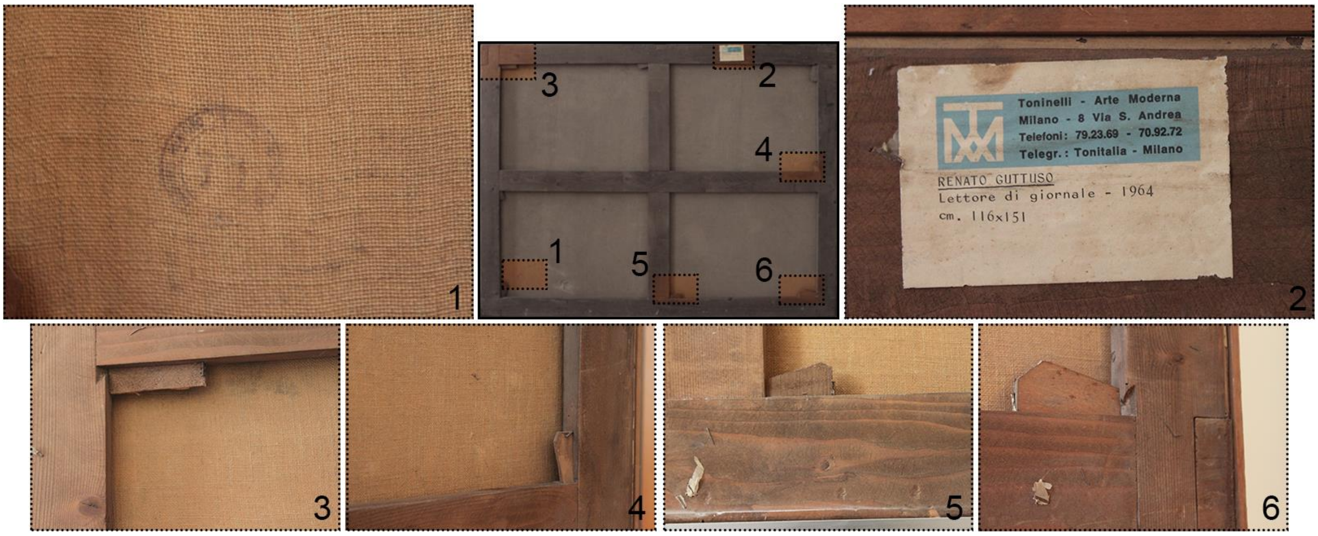

Fig. 3: Back details: 1| Canvas texture; 2| Toninelli Gallery label; 3-6| Frame single-corner strips, © Authors, 2025

To this end, an operational methodology consisting of five main steps has been developed to obtain high-quality, geometrically accurate three-dimensional models (fig. 4).

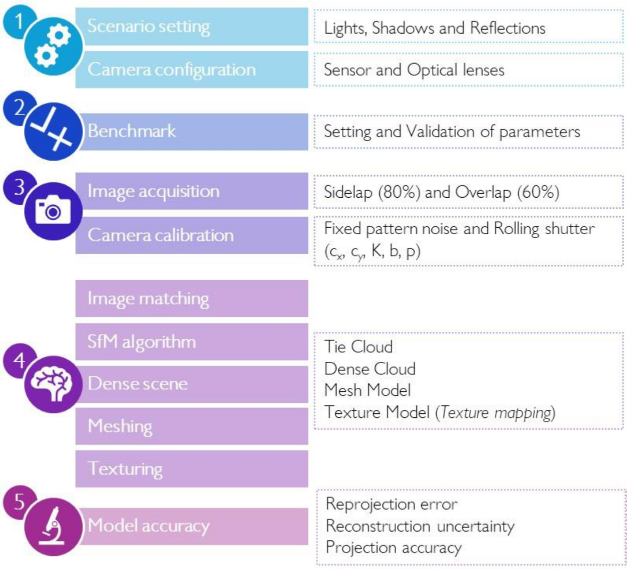

Fig. 4: SfM workflow for paintings, © Authors, 2025

The first step -scenario setting and camera configuration- is the most critical part of the entire process.

In fact, during the scene capture procedures, some algorithms explicitly state that flat objects, such as a painting on paper, and environments with shaded areas—such as those that can be created inside enclosed spaces with artificial lighting or caused by the operator during the acquisition—can negatively affect the success of the model. Therefore, this first phase required particular attention to the setup of the environment for image acquisition to minimize environmental disturbances that could have compromised the successful outcome of the methodology.

It involves preparing the environment for image acquisition, focusing on lighting and camera settings. The goal is to minimize environmental noise that could compromise the methodology's success. During scene capture, identifying shadow areas -common in enclosed spaces with artificial lighting- plays a key role in ensuring the quality of the model. Given that the artwork is movable, its portability allows for a customized setup that minimizes irregular lighting and unwanted reflections, enhancing the digital capture of the artwork.

In this case study, the ideal placement was near large windows to ensure the use of only natural light. Additionally, the optimal orientation artwork's relative to natural light was determined, with support from a side shield made of a matte black panel.

This shield, created using a black roll-up and positioned between the artwork and window, was designed to diffuse the light, reduce shadows, and minimize reflections on the camera, which was used without a flash (fig. 5).

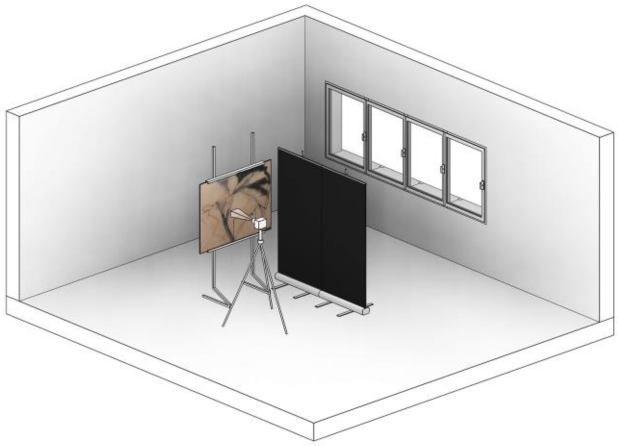

Fig. 5: Setup for photogrammetric acquisition with natural light and black panel, © Authors, 2025

In this phase, the technical parameters of the acquisition tool must also be defined, including the sensor type and optical lenses. In this case, a Canon EOS850D camera with an EF-S 18/55mm f/3.5-5.6 STM lens was used on an adjustable tripod with a level. The 22.3x14.9 mm CMOS sensor was selected for its characteristics: despite being less sensitive in low-light conditions, it is well-suited for static objects.

The second step –benchmark- focuses on defining and verifying the parameters that affect the entire process. Specifically, key operational parameters are set, such as the distance between the camera and the object and the image resolution. In detail, the camera equipped with the chosen lens, with an ISO of 3200 F4.5 1/60, allowed for managing the focal distance of 18mm, about the very close distance to the object (50cm) required for the radiometric characteristics of the painting, shadow control, and focus. After taking test shots to assess the image quality, the initial results were carefully analyzed to ensure the absence of systematic errors, such as distortions or blurring caused by improper camera settings. Subsequently, to verify the accuracy of the setup, the GSD (Ground Sampling Distance) was calculated, which returned an average error between the centers of two pixels of less than a millimeters (0.00100m), which more than met our expectations (tab. 1).

Test shots are taken to evaluate image quality, ensuring proper lighting, sharpness, and the absence of unwanted reflections and shadows. The initial results are carefully analyzed to ensure no systematic errors, such as distortions or blurring, caused by inappropriate camera settings.

Tab. 1: GDS Calculation

Sw	22.3	=sensor width of camera (mm)
FR	18	=focal length of camera (mm)
H	0.50	=shot distance (m)
imW	4752	=image width (pxl)
imH	3168	=image height (pxl)
GSD	**0.0067**	**=Ground Sampling Distance (cm/pxl)**
Dw	0.200	=image footprint width
DH	0.300	=image footprint height

The third step -image acquisition and camera calibration- involves the actual image capture and camera calibration to ensure model accuracy. During image capture, which is performed orthogonally to the artwork's surface, it is ensured that each image has 80% sidelap and 60% frontal overlap. Some frames must be captured by adjusting the shooting angle by ±60/70° to improve the three-dimensional data.

In this phase, camera calibration is also performed, automated within the photogrammetry pipeline through the *CameraInit* node of the Mushroom software, to correct errors such as fixed pattern noise and rolling shutter. The calibration parameters (cx; cy; K; b; p) further optimize the image quality and fidelity. In the case of *"Uomo che legge,"* 485 frames were captured with a resolution of 4752x3168 pixels.

The fourth step -the SfM algorithm- is the core of the photogrammetric process, where the collected data is handled to generate an accurate 3D model. Using Mushroom's open-source software, homologous points between the acquired images are automatically identified through feature-matching algorithms (image matching). This generates a sparse point cloud of 56,674 points (Tie Cloud).

This initial representation quickly assesses acquisition quality and identifies gaps or errors in coverage. Subsequently, a Dense Cloud of 4,604,391 points was generated, representing the geometric details of the artwork with high precision.

This dense point cloud serves as the foundation for further artwork analysis. The dense point cloud created a 3D polygonal mesh model with 2,000,000 triangular faces.

The final step of the SfM phase involves applying textures to the mesh model using Texture Mapping.

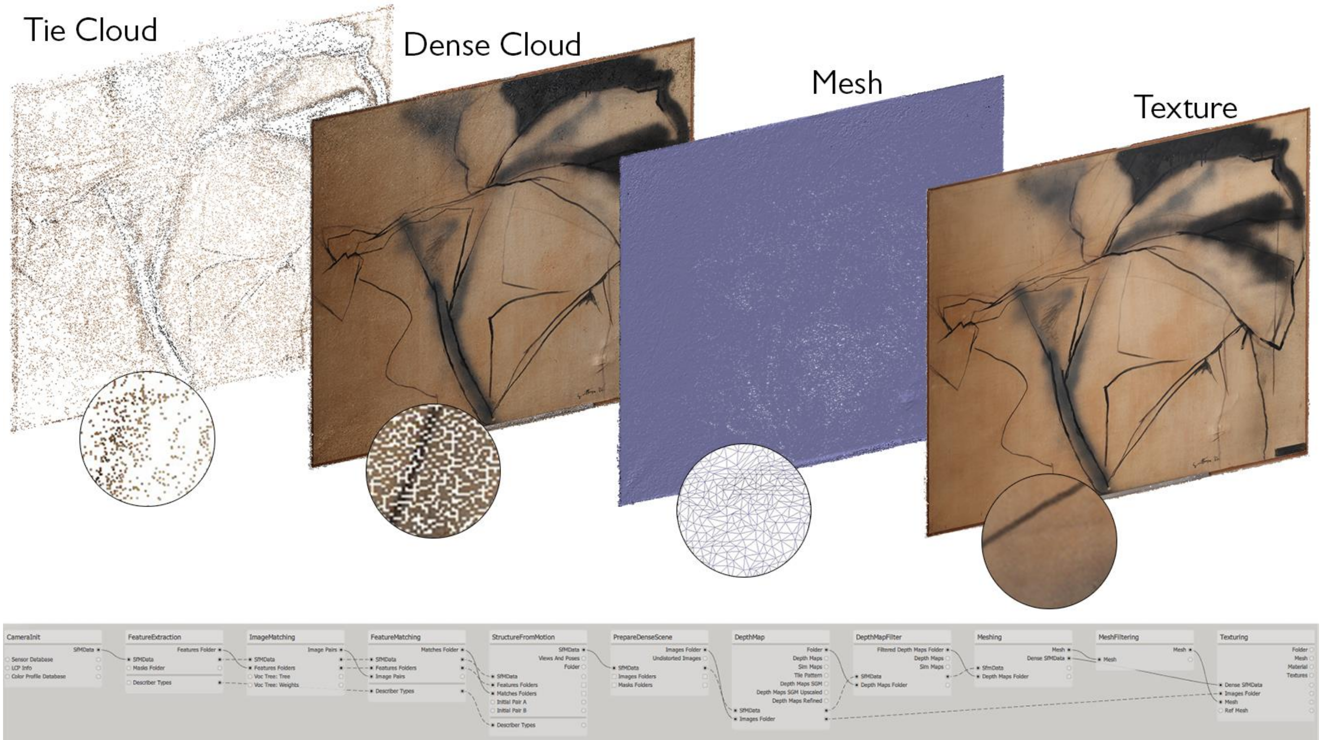

Fig. 6: SfM process: 3D model generation by Meshroom, © Authors, 2025

This technique maps the original images onto the mesh, producing a highly photorealistic model (fig 6).

Several parameters were analysed in the last step -Model accuracy- to evaluate the model's accuracy. The reprojection error averaged less than 0.5 pixels, confirming excellent camera calibration and high-quality point correspondences. Low reconstruction uncertainty indicated the model's geometric precision. High projection accuracy showed strong alignment between the 3D model and original images, ensuring a precise and reliable representation suitable for conservation analysis and diagnostics.

4. Analysis of geometric/material discontinuity

The point cloud from digital photogrammetry enables non-invasive analysis through each point's spatial (x, y, z) and color (R, G, B) attributes. This data identifies material discontinuities and geometric deformations, providing a foundation for assessing conservation status and guiding restoration efforts.

The surface S of a paper painting, defined as z=f(x;y), may show geometric discontinuities indicating local continuity variations. Elevation discontinuities are marked by changes in z along x, y, while slope discontinuities involve variations in the derivative $\sqrt{(\partial Z/\partial X)^2 + (\partial Z/\partial Y)^2}$, representing surface inclination. Curvature discontinuities, involving changes in principal curvature, are harder to detect. Identifying discontinuities from point clouds obtained via digital photogrammetry is complex but crucial for understanding a painted surface's deformation and degradation. Direct analytical methods calculate local discontinuity indicators using interpolating functions, such as Breakline Modelling (Briese, 2004) and 2D-3D Feature Extraction (Alshawabkeh et al., 2006). Indirect methods estimate continuous surfaces to identify discontinuities through their intersections, particularly effective for slope and curvature detection (Remondino et al., 2011). Combining these methods enhances analysis accuracy (Tucci et al., 2014).

The pseudo-planarity of painted surfaces allows for direct and indirect methods to assess geometric discontinuities. Software like Cloud Compare, using tools such as the MPlane plugin, interpolates point clouds to generate reference planes and calculates point-to-plane distances. These distances are visualized through color mapping, highlighting elevation variations and discontinuities. Visual gradients provide a clear and effective representation for monitoring the

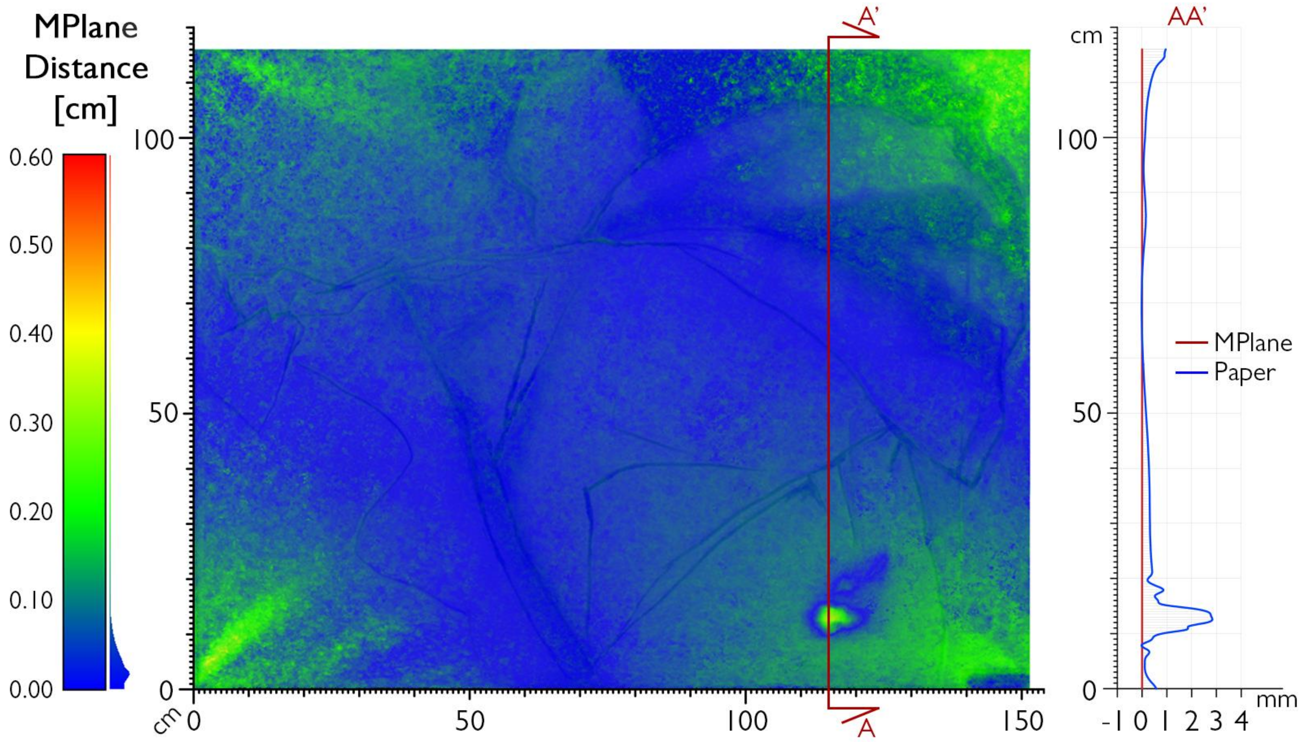

Fig. 7: Geometric discontinuity analysis: elevation deviations from the MPlane; surface deformations along section AA', © Authors, 2025

artwork state conservation before the restoration intervention.

Figure 7 highlights the pseudo-planar regions of the painting, with noticeable discontinuities primarily at the corners of the rectangular surface, showing variations of approximately +3 mm in the area affected by anthropic damage. Blue areas indicate the absence of deformations, while the green areas represent moderate planar irregularities. The most critical issues are concentrated along the sheet's edges, where mechanical stress from improper frame tensioning has taken a toll, and in certain central zones, likely affected by accidental impacts. These findings emphasize underlying structural issues and provide a valuable foundation for targeted restoration efforts.

Material discontinuities include alterations in the surface and composition.

Point cloud analysis revealed pigment texture variations and adhesion loss, with microscopic lifting evident in areas of higher graphic density due to titanium-based pigment stress.

Photogrammetry also identified surface deposits, diminishing the artwork's brilliance.

Integrating the digital photogrammetric model with chromatic data also enabled the identification of areas affected by fading, opacification, and pigment degradation, such as black zones shifting to grey due to light exposure and aging. The qualitative colorimetric analysis is based on the understanding that the chromatic elements used by the artist are essentially two: the white paper support and the black titanium-based pigments.

A procedure was defined -described in the workflow in Figure 8- to detect chromatic discontinuities using the RGB channels, which involves importing the textured image of the digital model obtained through Mushroom into Photoshop.

Within Photoshop, the three-color channels - Red, Blue, and Green- are separated, and the tonal distribution (Gaussian) histogram is analyzed for each one. By working on the histogram, the standard deviation of the Gaussian curve is reduced to:

- decrease the blurring effect,
- preserve more color variation,
- enhance chromatic contrasts in each color channel.

This process facilitates, for red, the identification of warm color areas and the reading of underlying layers; for blue, the detection of cool tones and the visualization of any surface patinas;

for green, the identification of transitional colors and phenomena not included in the previous two.

After processing the histograms, the three channels are merged again to obtain a qualitative false-color image.

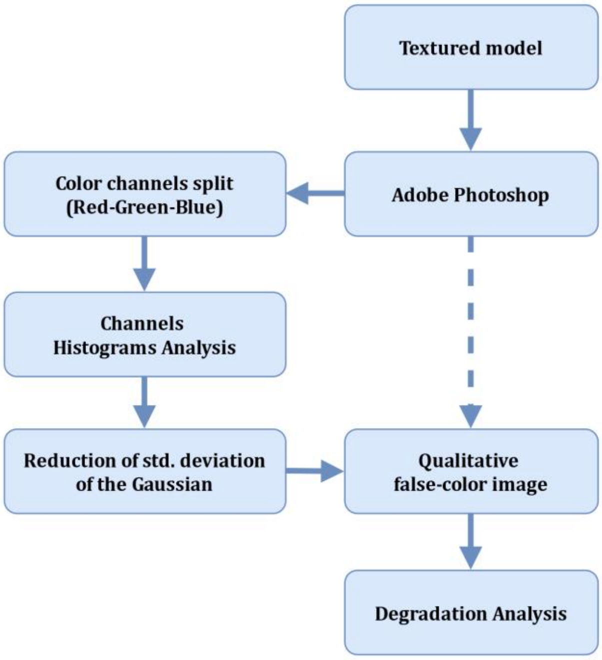

Fig. 8: Workflow to detect chromatic discontinuities using the RGB channels, © Authors, 2025

The result of the process is shown in the figure 9. The image allows for the highlighting of several features, and the chromatic discontinuities of the painting are represented. In the upper areas on the right side, red and white tones are visible, indicating significant alterations likely due to pigment lifting or surface deposits, probably caused by environmental factors such as intense light or fluctuations in humidity. The bright, well-defined diagonal lines at the center, rendered in red and white tones, suggest areas of material stress, potentially corresponding to cracks or pigment detachment from the support, worsened by mechanical forces or chemical changes. Significant variations are also visible in the lower corners and along the edges, where vivid tones reflect mechanical tensions caused by factors such as uneven frame tensioning or accidental impacts. In contrast, more uniform blue and green tones represent pseudo-planar areas where the surface appears stable and consistent, with minimal material variations.

However, the transitions between these stable zones and the more altered ones—marked by abrupt shifts from cool to warm colors—indicate gradual changes in surface consistency or structure, which may be indicative of localized degradation.

This chromatic analysis provides a vivid (*enárgeic*) representation of the painting's conservation state, making both geometric deformations and material discontinuities readily apparent. The collected information offers critical insights for designing targeted restoration interventions and monitoring the evolution of degradation over time.

5. Conclusions

The case study on *Uomo che legge* by Renato Guttuso highlighted how the Structure from Motion (SfM) methodology can be understood as a form of visual *enárgeia*, making otherwise imperceptible details visible and vividly comprehensible. Digital photogrammetry and three-dimensional analysis enabled the precise detection of geometric deformations and material discontinuities, clearly representing the artwork's conservation state.

This ability to "bring the artwork to life," revealing structural and chromatic alterations through detailed and intuitive visualizations, underscores the potential of SfM not only as a technical tool and a means to enhance visual understanding.

The procedure presented, which is innovative in the context of the case study involving paper paintings, has several strengths. First and foremost is the cost-effectiveness of the surveying equipment, which does not require integration with other costly technologies, as well as the reliability of the results, especially in terms of geometric deformations.

One weakness lies in the inability to analyze the painting from a material point of view, as the procedure mainly allows for qualitative analyses.

A possible future development involves comparing the reliability of results on paper-based operas of significantly different sizes, such as a page from a medieval manuscript and a sheet of historical cartography.

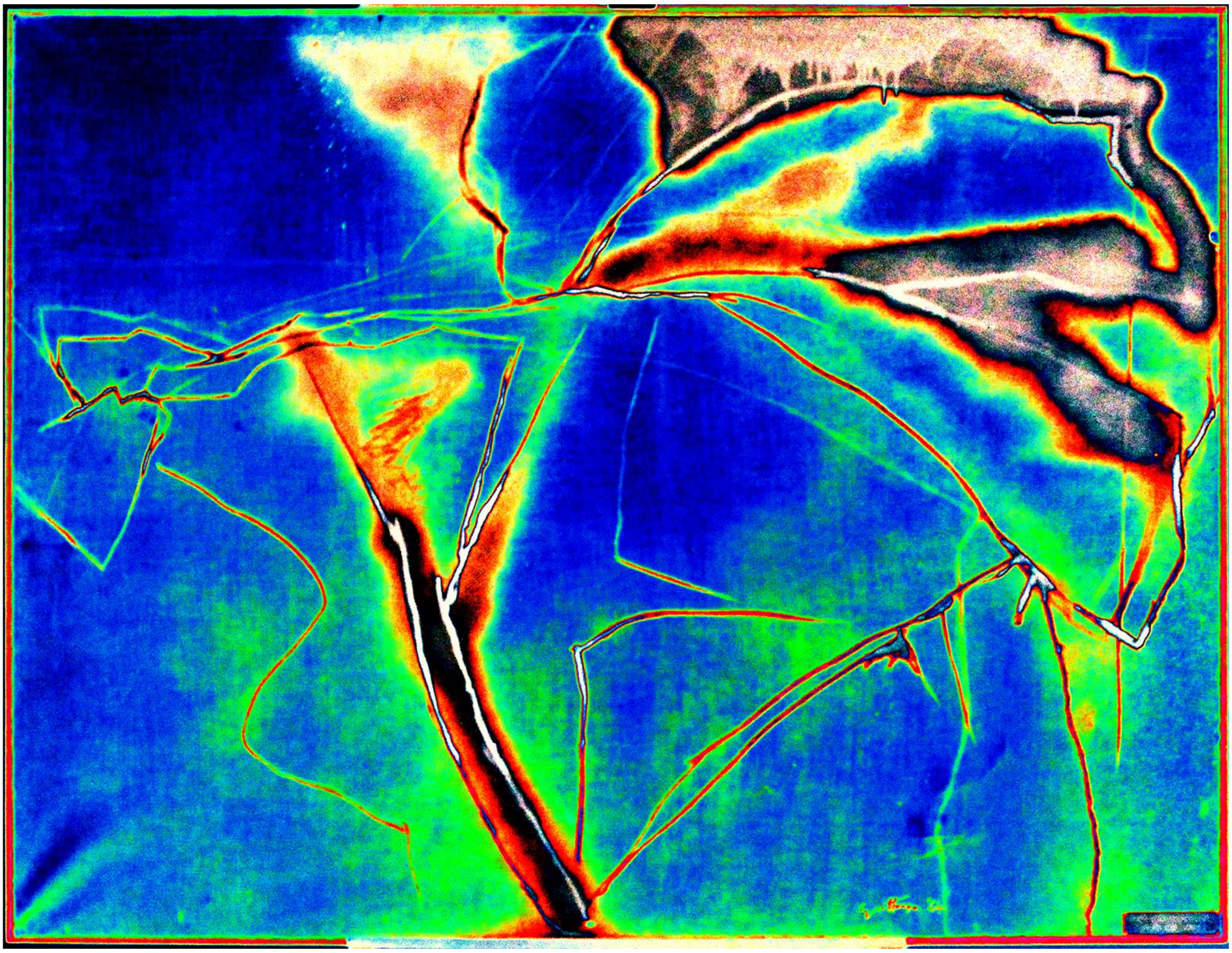

Fig. 9: Material discontinuity analysis: adhesion loss and surface alterations, © Authors, 2025

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