KNOWLEDGE AND DOCUMENTATION OF RENAISSANCE WORKS OF ART: THE REPLICA OF THE “ANNUNCIATION” BY BEATO ANGELICO

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ABSTRACT:
The *Annunciation* by Guido di Pietro from Mugello, known as Beato Angelico, is a wide tempera painting with some fine gold foil placed on a wooden support, today hosted at the Museum of the Basilica of Santa Maria delle Grazie, in San Giovanni Valdarno. On the occasion of the exhibition “*Masaccio e Angelico. Dialogo sulla verità nella pittura*”, the museum asked to the Department of Architecture at the University of Bologna to develop a digital high-resolution surrogate to favour deep investigations, to plan restoration and to simply tell the stories behind the artwork. Two tasks were accomplished: to let visitors discover the secrets in the painting and to let scholars study the artwork, to better understand the masterpiece. This paper introduces the outcomes of the research developed to digitize the *Annunciation,* following a dedicated pipeline developed to improve the fruition of its digital replica, originated from different input sources, and surrogating the user experience on the real object. This work presents a method for the 3D reconstruction of the surfaces based on different techniques for elements with different depth resolutions (i.e., the painting and the wooden frame) which combine photogrammetry and photometric stereo exploiting both procedures and pushing forward the boundaries of Gigapixel Imaging and photogrammetric-based 3D model representation.

1. INTRODUCTION

Painting digitization is a well-established technique for the knowledge, analysis, and communication with outstanding results since more than fifteen years ago (Borgeat et al., 2007). In recent times, due to the progresses in the automatic photogrammetry techniques (Remondino et al., 2006), this solution quickly succeeded to the first one, with many excellent results (Barazzetti et al., 2010; Pamart et al., 2017).
However, the focus of the developed workflow was on the coupling of shape digitization using photogrammetry with multispectral imagery acquired using spectral techniques.
This approach is excellent to generate data useful for professional operators (restorers, art historians, etc.), and for painting analysis, but it leaves many unsolved problems concerning the painting safety, the digital visualization, the communication, and the use by non-specialists of the data sets acquired. Furthermore, the acquisition operations are often complex, and the data interpretation could be difficult, also requiring the human intervention with possible errors. Thence the correct color extraction to properly visualize the artwork on the screen (usually an RGB-based device) is an operation requiring a high degree of options making the results frequently highly biased when compared to the original. More in general, the correct color acquisition and reproduction problem is usually underestimated (Gaiani et al., 2021) with a very low number of studies focused on this topic (Dhanda et al., 2019). The evaluation of the incorrect visualization, often due to color management exploiting the common rendered sRGB color space that leads to non-consistent saturated colors such as cadmium yellow and cobalt blue, among the grayish colors and related issues, is completely missed.
Finally, a main issue consists in the lack of the reproduction of the full optical properties of the painting: the typical output is a single texture mapped polygonal model reproducing the diffuse component of the reflection only (Pelagotti et al., 2009) but specular component, glossiness, refraction, roughness, subsurface scattering, transmission, and other fundamental phenomena to correctly perceive the painting are completely missed.

In this paper we present a technique aiming to overcome these problems, developing a digital high-resolution surrogate to consent deep investigations, to plan restoration or to simply tell the stories behind the artwork. Two tasks had to be accomplished:

- to let visitors discover the secrets in the painting,
- to let scholars study the artwork to better understand how the artist worked, how restorations were performed, if some “pentimenti” could be explained, and to determine the conditions of the painting preservation and to support further restoration interventions.

Since 2010, the research team based at the University of Bologna has developed a semi-automatic pipeline to digitize artworks for the purposes of replicating and communicating them to museum visitors, art historians, restorers and all the other possible roles involved in painting activities, accurately reproducing full optical properties of the artefact. Our goal was the reproduction of the way in which the painting is perceived by the human vision, surrogating the *total appearance* of the real object (Happa et al., 2012), at a resolution of 25 μm.
Starting from solutions developed with a specific focus on drawings by Leonardo da Vinci (Gaiani et al., 2018), the so-called *ISLe* (*In Sight Leonardo*), we improved the past work to consider problems and differences related to the paintings, creating the new *AnnunciatiOnApp*.
Among the many issues to be addressed and solved to transpose the painting into a digital form, in this paper we introduce problems and solutions related to the acquisition stage.
In detail, the paper focuses on the transition from artworks on paper sheets variable in size among an A5 and A3 format (the drawings), to an artifact sized 2350x2430 mm, leading to a surface area approximately 60 times larger, and from surfaces featuring pen or pencil marks around 5÷10 μm thick, and a roughness of the paper which rarely exceeds a tenth of millimeter (the drawings) to features varying between 25 μm and a few millimeters (the painting) while the frame thickness ≈ 100 mm. required the development of new techniques and tools.
The two most common solutions used to digitize paintings were the starting point of this development:

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- Gigapixel images, accurate in image resolution, but limited to a simple reproduction of the apparent color, and without any ability to show the three dimensionality of the painting and its reflectance properties (Cabezos-Bernal, 2021a),
- Photogrammetric-based 3D models, accurate in the metric and 3D features reproduction, but generally not in the color replica and, in any case, unable to reproduce most of reflectance properties (Remondino et al., 2011).

AnnunciatiOnApp integrates the two techniques to exploit their advantages and to discard their deficiencies.

Our case study, that could be defined as a superset of all the difficulties that we can find in the acquisition of a painting (large size, specular reflection, cast shadows on the painting, impossibility to move it outside the Museum, presence of frames of significant thicknesses), is the *Annunciation* in San Giovanni Valdarno authored by Fra Angelico, a Early Renaissance Italian painter of the, described by Giorgio Vasari in his *Lives of the Artists* as having "a rare and perfect talent" (Vasari, 1965). The occasion for this work raised for the exhibit *Masaccio e Angelico. Dialogo sulla verità nella pittura*, opened at the Museum of the Basilica of Santa Maria delle Grazie in San Giovanni Valdarno, from September 17, 2022, to February 5, 2023.

Figure 1. The *Annunciation* by Beato Angelico at the Museum of the Basilica of Santa Maria delle Grazie,

2. THE CASE STUDY

The *Annunciation* preserved in San Giovanni Valdarno comes from the nearby Convent of San Francesco di Montecarlo and it is one of the three "twin" tables painted by the Dominican friar Giovanni da Fiesole, known as Beato Angelico, together with the one in the Prado Museum (from the church of San Domenico di Fiesole) and of the other in Cortona (Strehlke, 2022). The painting is organized in two parts: the upper panel with the Annunciation, and the lower *predella,* which depicts the events that follow the moment of the Annunciation through five different small tables. Dated back to 1430-32, the Annunciation is a 1950x1580 mm wide tempera painting with some fine gold foil placed on a wooden support and it represents the scene narrated by the evangelist Luke, where the Archangel Gabriel is represented in the act to foretell to the Virgin Mary that she would become the mother of Christ (Figure 1). The years in which the painting was made correspond to a transitional period in Florentine painting. The challenge faced by Giovanni da Fiesole was to combine the new Renaissance principles, such as perspective construction and attention to the human figure, with the old medieval values, such as the didactic function of art and the mystical value of light confirmed using a very strong luminosity capable of eliminating shadows, together with the use of bright and unnatural colors. The representation is enriched by many Christian symbols: in the center there is the Christ column, a reference to the trunk of the cross and the tree of life, the splendor of gold alludes to the divine light, the palm is the emblem of victory over sin and death, but it also alludes to the Passion of Christ. Those details entail a narrative contrast between the bright colors of the Archangel Gabriel and the Virgin with a dark room in the foreground, under the *loggia*.

The paintings in the *predella,* 300x150 mm each, reveal the autography in the general conception and in some higher quality scenes while in the others the intervention of the painter Zanobi Strozzi, one of the main collaborators, is probable.

The wooden frame, coated with gold foil for the greater part, presents some minor painted areas: two fluted and rudentated side pillars painted in white and a concave surface connecting the painting with the upper frame, painted in blue with a star pattern, and a planar pendentive painted in red with phytomorphic motifs in gold foil. It presents a bounding box of 2350x24300x380 mm and it is displayed in the center of the main wall of the exhibition room, at a height of 1100 mm.

3. METHOD AND TECHNIQUES

Fra Angelico's *Annunciation* was digitally acquired following a dedicated pipeline exploiting three different technologies to get the final 3D model: gigapixel imaging (Kopf et al., 2007) to achieve the desired resolution of the images of the painted parts (reference), automatic photogrammetry to acquire the shape of the frames and the painted tables and photometric stereo (Woodham et al., 1980) to reconstruct optical properties of the surface of the painting.

Several investigations demonstrated that automation in image-based methods reached a very efficient level in the CH field (Gonizzi Barsanti et al., 2015, Apollonio et al., 2021). Open issues are well surveyed and bounded (Remondino et al., 2017).

The two main panels of the painting, the top roundel and all the five scenes in the *predella* were acquired considering the characterization of the surface through the application of photometric stereo imaging while the wooden frame was acquired completely through the digital photogrammetry.

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Photometric stereo returns a series of fundamental data to reconstruct the optical properties of a surface:

- albedo, which estimates the illuminance matrix by solving a non-linear least square problem;
- normals, calculated through the influence of the different directions of light on the pixels of the resulting image, to define the fine mesostructure of materials;
- depth recovered from the estimated normal vector field, to define the coarse mesostructure of materials;
- specular reflection, subsequently detailed also to create the simulation of the gold leaf parts.

The method used for the *Annunciation* follows the original stereo photometric formulation with the light sources assumed at infinite distance and the orthographic camera, but instead of only three images to solve the photometric problems, it uses eight.

Results from the two separate paths were merged into a unique 3D model aligning textured meshes coming from the photogrammetric process and from the photometric stereo using ICP techniques (Besl & McKay, 1992) and discarding overlapping parts. The whole pipeline is presented in figure 2.

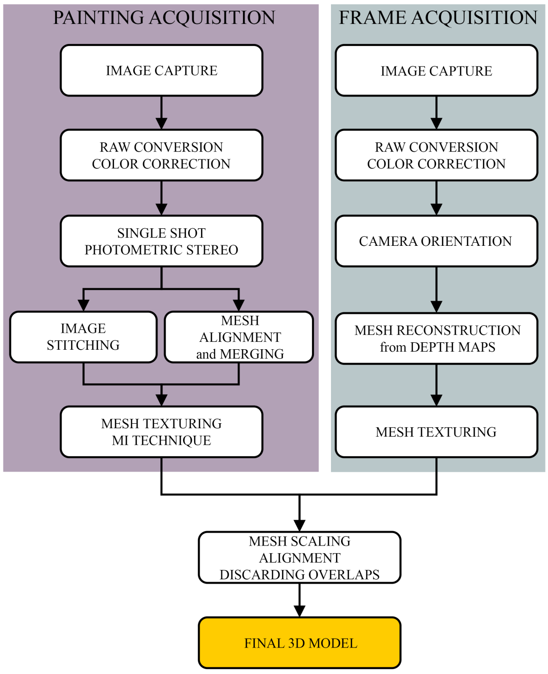

Figure 2. The acquisition and 3D modeling workflow.

4. THE PAINTING AQUISITION

4.1 Equipment

The photographic equipment consisted of a Hasselblad H6D-400C multi-Shot medium format camera, with a 53.4x40 mm Sony CMOS sensor made of 11600x8700 pixels (4.6 µm pixel pitch), for a maximum resolution of 23200x17400 pixels (through 6 shots) with non-interpolated 48-bit color depth. The Multi-Shot technology allows to get the effective color at each pixel location (GRGB) without moiré interference and a 4x resolution (i.e., about 400 Mpixel) through four shots taken by moving the sensor by half a pixel at a time. In our case, the multi-shot resolution was used. The lens used was a Hasselblad HC MACRO 4/120 II 120 mm that produces very sharp images maximizing resolution (using a f/11 diaphragm aperture to, it presents a Modulation Transfer Function (MTF) at infinite focus setting equal to 95%), and it well supports the shooting method chosen consisting in shooting while moving the camera parallel to the painting, as in (Cabezos-Bernal et al., 2021a). Finally, it minimizes the typical Depth of Field (DoF) effects when images are acquired with macro-lenses (Farella et al. 2022). The depth of field of the HC MACRO 4/120 II is comparable to that of an 80 mm lens for a 35 mm equivalent, allowing to overcome problems related to the table of painting deformations.
To ensure the correct color reproduction we used target-based color correction exploiting an in-house software solution (Gaiani, 2017) and as reference color target the popular Calibrite ColorChecker Classic (MacCamy, 1976).
As far as lighting is a paramount matter when dealing with artworks, we opted out for a *High Flux LED* white light single light diode: the Relio^2 light (www.relio.it), an illuminator that emits continuous spectrum light at a CCT of 4000°K and features a Spectral Power Distribution that indicates high chromatic reliability at all wavelengths. It brings many advantages: a very bright source (luminosity of 40,000 lux at 250 mm), light spectral properties consistent from shot to shot and from year to year, and a limited weight and space for the whole system.
Moreover, it does not present IR & UV wavelengths light components, which can be extremely harmful for paintings.

Figure 3. The custom stand in action.

Finally, the exposure to light of the painting, during the shooting, was approximately 60 lux•hour/year, equivalent to just over an hour of exposure to the public, ensuring levels of illumination during the photoshoot very low and a safe acquisition process, following the UNI standard 10829/1999.
From an operational point of view, a new stand was designed and built to support the thirty-two Relio^2 LED lights and to permanently connect them to the digital camera, allowing vertically and horizontally rigid movements (Figure 3). This light configuration grants a uniform illumination of the framed picture area, to avoid the problem of specular reflections of the varnish covering the tempera and the gilded areas of the painting and the frames. The whole stand structure was produced modifying the commercial Manfrotto 816 Stand Salon Column equipped with a Manfrotto 410 rack head. To this 2800 mm high rig, was added a structure of four removable arms in aluminum profiles, braced with brackets and tie rods to guarantee the absence of any type of bending. The sliding supports made of ABS filament, resistant to the heat emitted by the light sources, were housed on the tubular frames. To ensure the preservation of the parallelism between the camera and the plane of the painting, two Leica Disto D2 laser distance meters have been placed on the two side arms capable of guaranteeing the distance of the camera from the painting and the perpendicularity between the axis of the camera and the table with an accuracy of ± 1.5 mm. The stand was then mounted on anti-vibration supports to avoid blurring in the images related to these occurrences, significant in presence of floors such as those at the museum where the artwork is preserved.

4.2 Shooting techniques and camera network

The painting's panels were acquired shooting with locked exposure settings during the capture process, to keep the same brightness levels. The ISO setting was set to the value of 64 to minimize the noise. The aperture was set to *f*11 to maximize the lens sharpness, thus avoiding the negative effects of the diffraction of light that arise using too small diaphragm apertures. To avoid problems related to the acquisition from the same standpoint, consisting in loss of sharpness in off-centered shots zones of the painting and erroneous reconstruction of the optical properties of the surface using the photometric stereo due to the angular deviation between the camera sensor and the painting, the camera network consists in a series of shots moving the camera parallel to the painting and leaving the camera axis

perpendicular to the painting surface as in (Cabezos-Bernal et al., 2021a). Using this technique, the light reflected by the work will change between the shots, potentially producing slight differences in exposure and problems with specular reflections. Those issues were solved by the placement of LED light sources, which moved along with the camera.
The acquisition network to achieve gigapixel is, then, a multi-shot capture, with a minimum overlap of about 25% between adjacent pictures so that, by means of image stitching techniques, they can be joined to compose a higher resolution image. The pixel density was evaluated using the equation:

$$PD = \frac{S_r \cdot F_L \cdot U_f}{D \cdot S_w} \tag{1}$$

where PD = Pixel density (in ppi)
S_r = Sensor width resolution (in pixel): 23200
F_L = Focal length of the lens system (in mm): 120
U_f = Unit conversion factor: 25.4 for PD in inch (ppi)
D = Camera distance to the painting (mm): 1120
S_w = Camera sensor width (mm): 53.4

Starting from the planned resolution of 25 µm corresponding to 1016 dpi, it was planned a camera-to-surface of 1120 mm allowing a nominal resolution of 1182 ppi. The area covered for each picture is 500x375 mm. Because the true spatial resolution of a digital imaging system is characterized by two parameters: the number of pixels that a camera can acquire and the ability to resolve fine line pairs (a contrast gauge), we made sure to preserve PD measuring the MTF at different spatial frequencies, to determine how accurately our imaging device could reproduce the painting (Jacobson, 1995). The measurement was carried out following the ISO 12233 standard which analyzes the response of the system with respect to a slanted edge in terms of the rise distance of the curve as a function of the spatial frequency, expressed in units of cycles per pixel. We considered two parameters:

- MTF10: an indicator of the maximum resolution, although not always a reliable indicator of image sharpness since noise can strongly influence the results,
- MTF50: an indicator of the sharpness of cameras and lenses because model accurately two occurrences: the image contrast is half its low frequency or peak values, so details are still quite visible; the response of most cameras falls quickly in the proximity of this value.

The combination of camera, lights, and the custom rig we developed and used led to MTF 50 and MTF 10 values respectively estimated in 0.133, and 0.256 line pairs/pixel (Figure 4). The Effective Resolution R_e was evaluated as the product of Efficiency E by Nominal Resolution R_n from the equation:

$$R_e = E \cdot R_n \tag{2}$$

where

$$E = \frac{MTF_{50}}{C/P} = \frac{2 \cdot MTF_{50} \cdot H_s}{H_f} \cdot Px_{Nyquist} \tag{3}$$

and

$$R_n = \frac{H_s}{H_f} \cdot 25.4 \tag{4}$$

in which:
MTF_{50} = Spatial frequencies distribution where MTF is 50% of its low frequency value (in cycles/pixel)
C/P = Cycles/Pixel, a value to show how well pixels are utilized
H_s = Sensor height (in pixel)
H_f = Feature height (in mm), the height of an image in which efficiency is calculated
$Px_{Nyquist}$ = Pixel size at the Nyquist frequency (in mm).

The Nominal Resolution R_n is multiplied by 25.4 in the end to express it in pixel/inch instead of the original value in mm/inch. In our case, R_n was 1168 pixels per inch with a final measurable detail confirmed in 21 µm. Overall, two hundreds and seventy images were acquired for a total of about 106 gigapixels, corresponding to 26.8 gigapixels after their fusion.

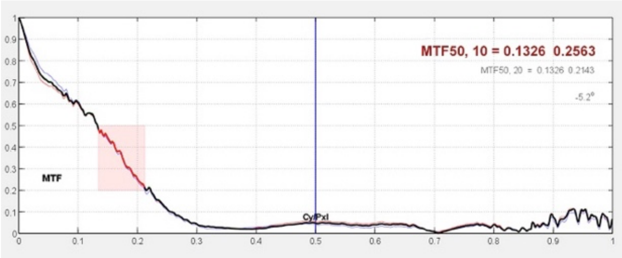

Figure 4. Measured MTF values.

The resulting camera network is represented in Figure 5. Nine pictures under nine different light directions of every portion of the painting were collected, totaling 270 Hasselblad's multi-shots for the painting (including the roundel and the *predella*), and keeping the position of the camera fixed with the axis perpendicular to the surface of the painting. The camera was remotely controlled by a laptop PC to minimize vibrations: one shot was taken with all the light sources on in the darked room, then eight light sets that were mounted at 45° and 20° with respect to the plane of the painting (four 45° light sources at 3,6,9,12 hours directions and four 20° light sources from the same directions) were cyclically activated. Each light source was made of 4 Relio² lamps. The 20° inclined set of lights was adopted to better orienting the output normals for specular surfaces and to better identify the critical angle of specular reflection for glossy materials.

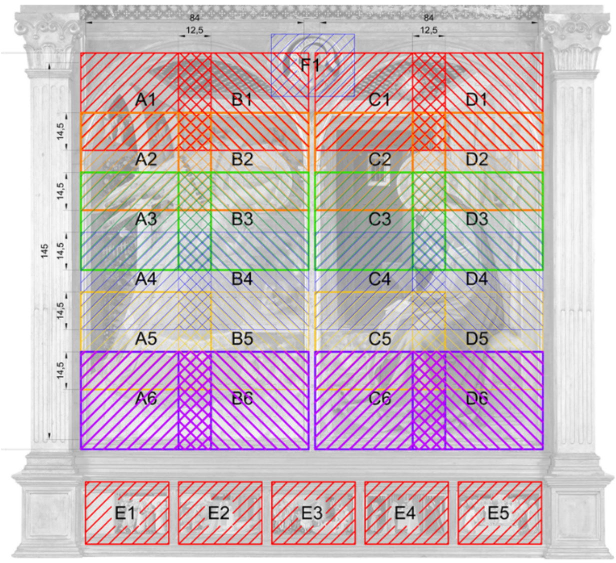

Figure 5. Camera network for the painting acquisition.

4.3 Workflow

4.3.1 RAW conversion and color correction

The acquired images in the Hasselblad RAW file format (.fff) were optically corrected, sharpened and colorimetrically corrected exploiting the Five Rules of Colorimetric Imaging expressed by Roy Berns (2015): D50 workflow; optimal exposure; color correction (CC) based on the minimization of the CIEDE2000 with outstanding lightness accuracy; calibration independent validation; color-coding space that does not clip scene colors. As CC we used the fully automated and consolidated color correction solution developed by our work group, called SHAFT (SAT & HUE Adaptive Fine Tuning) (Gaiani & Ballabeni, 2018). The final images were rendered in the DisplayP3 color space, as it correctly reproduces even the colors in the cobalt blue area, used in the painting.

4.3.2 Optical properties and small size geometric features acquisition

Optical properties and normal maps were reconstructed exploiting a photometric stereo application called *nLights* developed on top of the Matlab PSBox toolbox (Xiong, 2023).
To manage the outliers generated by many causes (self-shading, interreflections, non-Lambertian behavior, etc.) and to increase the accuracy of the results, the software make use of the eight images with constant lighting coming from four different directions at two different angles with the surface of the painting, as well as the nineth with the painting uniformly illuminated. The light direction detection is achieved using nine images of a chrome sphere. Redundant conditions are used to refine the results by progressively discarding the closest values. Function of the software are:

- Fit the circle of chrome sphere from manual extracted points
- Find lighting direction from given chrome sphere
- Estimate light strength or refine lighting matrix by solving a non-linear least squares problem
- Perform photometric stereo to recover albedo and normal map (a map which allows to reconstruct starting from the estimated normal vector field the coarse mesostructure)
- Specular reflection extraction from diffuse and albedo
- Recover depth map from estimated normal vector field.

Furthermore, *nLights* returns a 3D geometric representation of the shape of the painting panel, in the form of a geometric OBJ file, obtained from the depth map (Figure 6).

4.3.3 Mosaicking of gigapixel images and the meshes

2D images and 3D meshes matching and their alignment and fusion was achieved in three steps:

1. alignment and fusion of images through a feature-based stitching technique, structured on an improved ASIFT detector/descriptor, generating correspondences with other images well distributed over the entire area of the image (Morel & Yu, 2009). Other improvements over the well-established SIFT-based techniques consists in: outliers rejection through the MSAC algorithm (M-estimator SAmple Consensus) (Torr & Zisserman, 1999) more accurate than the canonical RANSAC solution before the homography search; global alignment through bundle adjustment techniques in order to eliminate mis-registrations between all pairs of images (the process implemented, led to a mean reprojection error equal to 0.684 pixel); image blending and merging, based on the leveling technique by Lempitsky & Ivanov (2007), which consists of an optimization of the mosaic of the images using the Markov Random Field technique and a subsequent modeling using a colorimetric continuity parameter, of the need for leveling between the texture patches in the seams;
2. alignment and fusion of the meshes produced from the photometric stereo process using the Iterative Closest Point algorithm for alignment and a volumetric technique based on the Marching Cubes algorithm for fusion (computationally expensive, but not sensitive to the residual inaccuracies of the previous alignment) (Curless & Levoy, 1996).
3. alignment of the images to the 3D mesh performed by exploiting registration methods on a statistical basis based on reciprocal 2D/3D information (*Mutual Information, MI*). We used the solution developed by (Corsini et al., 2009) and implemented in Meshlab to achieve a reasonably exact convergence to the alignment solution.

The final resolution of the painting's parts is reported in table 1.

Painting part	Resolution		Mosaic output resolution
	Shots	in Gpixel	In pixel
Top roundel	9	3.6	23200x17400
Left panel	108	42.8	43891x76231
Right panel	108	42.8	44137x76448
Predella	45	16.1	23200x17400x5

Table 1. Gigapixel resolution for the painting's parts.

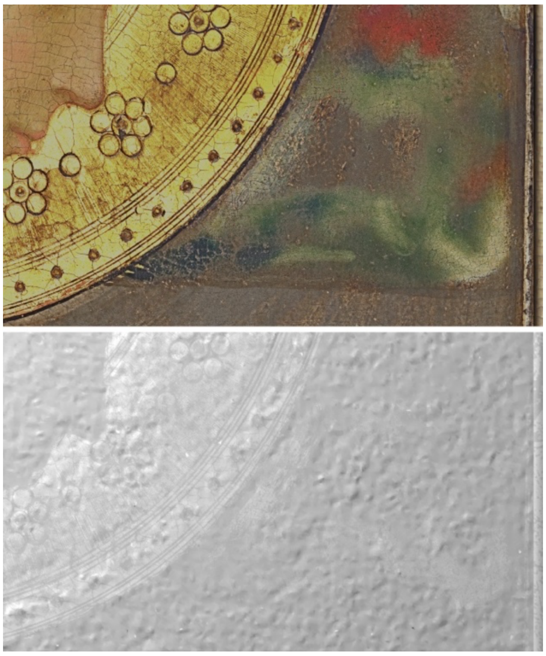

Figure 6. Macroscale geometry from photometric stereo.

5. THE FRAME ACQUISITION

The photogrammetric 3D acquisition of the frame had two objectives, both quantitative and morphological:

- the first consisted in planning the network that would guarantee a geometric resolution of 0.1 mm.
- the second had to do with the completeness of the survey of the visible areas of the artefact and the numerous undercuts present in the frame due to the presence of moldings, relief parts (capitals), as well as high specularity areas (gold foil) that usually lead to poor reconstructions in morphological terms (high noise and empty areas).

5.1 Equipment

The adopted equipment was a full-frame digital single-lens reflex (DSLR) camera, the Canon EOS 5D Mark III (CMOS sensor, frame resolution 5760x3840) with Canon EF 100 mm f/2.8 Macro USM lens with a circular polarizer filter applied with the aim to attenuate specular reflections, as well as a remote controller to avoid blurring and micro-blurring effects.
To perform long exposure times two tripods were used: a telescopic Manfrotto 1004BAC BK (max. height: 3660 mm) and a lighter, more portable, Manfrotto MK compactacn-BK (max. height: 1550 mm) for lower parts of the artwork.
The active sensor employed for the measurement of a set of relevant points on the surface of the frame was a Faro Focus 3D

X 130 laser scanner, offering a lateral resolution of 2 mm at 10 m and a depth measurement uncertainty of 0.15 mm.

5.2 Shooting techniques and camera network

To design the camera network and the shooting techniques as first the Ground Sampling Distance (GSD) was evaluated from the equation:

$$GSD = \frac{S_w \cdot D}{F_r \cdot imW} \tag{2}$$

where S_w = Camera sensor width (mm): 36
D = Camera distance to the canvas (mm)
imW = Image width (pixels): 5760
F_r = Focal lenght of the lens system (mm): 160

To fill the condition to have a minimal resolution of 50 µm/pixel we fixed the camera distance to the canvas to 700 mm allowing a GSD of 28 µm/pixel.

Considering the image capture for the photogrammetric process, we have mainly three types of issues: morphology (a), reflectance (b), and lighting conditions (c):

a) the shape of the frame presents high-frequency details, namely it is not a flat, or can be approximated to a 2D object. In addition, it presents architectural features with variations in depth that are ill-suited to the narrow depth of field typical of photographic shots in dim lighting and using macro lenses;

b) the frame presents high specular reflections, a problem that in the field of image processing also applied to photogrammetric techniques have been a source of different solutions (e.g., Guidi et al., 2014), all non-final. Gold foil areas show even more complex reflectance properties as its appearance changes with the change in the illumination direction (Arteaga et al. 2022).

c) the lighting system of the artwork is a major problem for the survey campaign due to the photosensitivity of the various materials used for the artwork because it was not possible to turn it off or dimmer it or change their direction. Illumination was provided by 3 LED spotlights (Philips CorePro LED spot ND 7-50W) placed at a height that ranges from 3450 and 3800 mm from the floor: one placed to the left and the other two to the right of the painting with convergent direction (figure 7). While the variation in illumination is considered negligible between the left and right sides, the same cannot be said for the variation that occurs vertically and consequently the exposure and focal aperture parameters had to consider this asymmetry.

From these considerations, it was decided to divide the photogrammetric campaign into two steps.

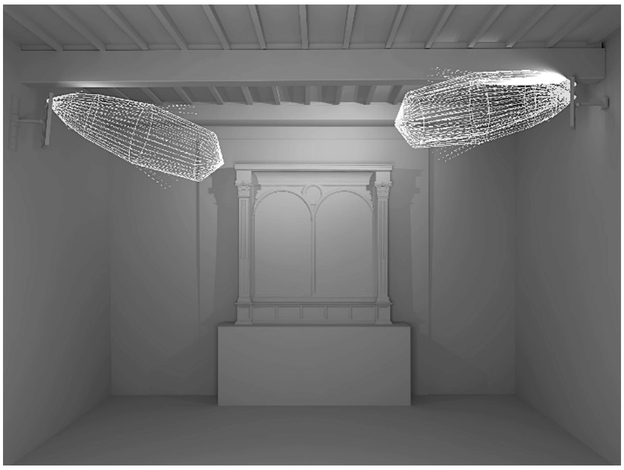

Figure 7. Shaded 3D model of the exhibition hall with light's distribution patterns of the three spotlights.

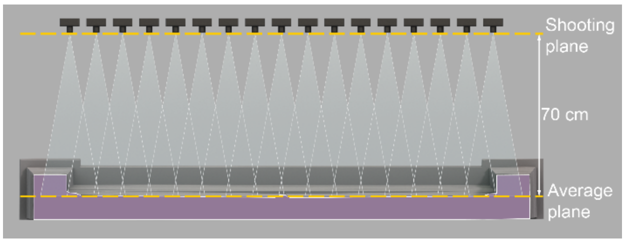

Figure 8. Horizontal section of the frame with first camera network capturing the central area of the Annunciation.

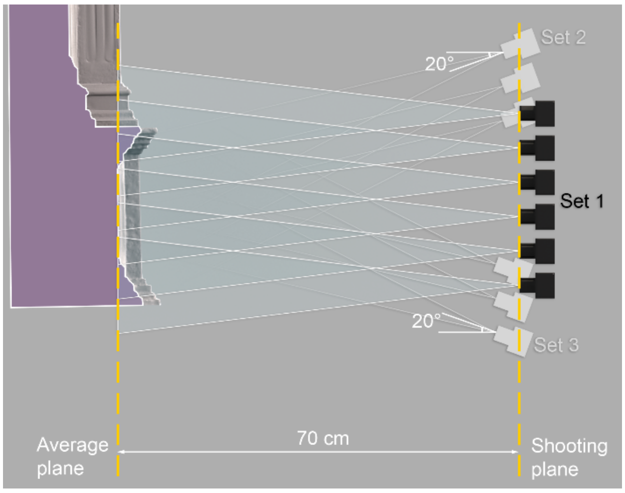

Figure 9. Camera network lateral view. Set 1 (102 shot) has optical axis horizontal. Sets 2 and 3 (102 frames) have a ± 20° rotation.

The first set of photos was aimed at capturing the 'system' defined by the frame and the paintings where are mainly the previously explained issues affecting the work of art. The set consists of 289 shots taken using a regular pattern (equal spacing) according to the classic boustrophedon progression from left to right and then up. The optical axis perpendicular to the average vertical plane of the artefact at 700 mm from the shooting plane to fit GSD with the required resolution (figure 8). Lighting conditions required to systematically check exposure and aperture for each horizontal row to achieve outstanding exposure. ISO speed was set to 200 while the f-number ranged from f/8 to f/11 with an average depth of field of 24,3 mm. This first network avoids the issue typical of the use of long focal lenses on almost-flat surfaces, i.e., a very narrow depth of field leading to blurred areas on oblique shots (Cabezos-Bernal et al., 2021b).

The second set consists of 570 shots organized as follows: 204 for the lower *predella*, 52 for each pilaster and 46 for the upper frame. For the *predella* the camera network does differ from what had already been done for the main painting. The moldings, which deviate up to 42 mm from the average plane of the five paintings, require to take oblique frames whose sharpness is much less than those with an optical axis perpendicular to the vertical plane (figure 9). For the areas with higher relief, namely the corner pillars, the capitals and the upper cornice, the following steps had to be taken: an average plane was established for the individual surfaces approximating to planes. Those areas were documented with shots perpendicular to their corresponding average planes and then, additional 20° tilted frames were introduced to fill in any oblique elements (moldings, carved flutes) and to facilitate the alignment between the sequences of volumes (figure 10). For the final calculation of the dense point cloud model and later for meshing, these additional frames (115), affected by imperfect sharpness, were disabled.

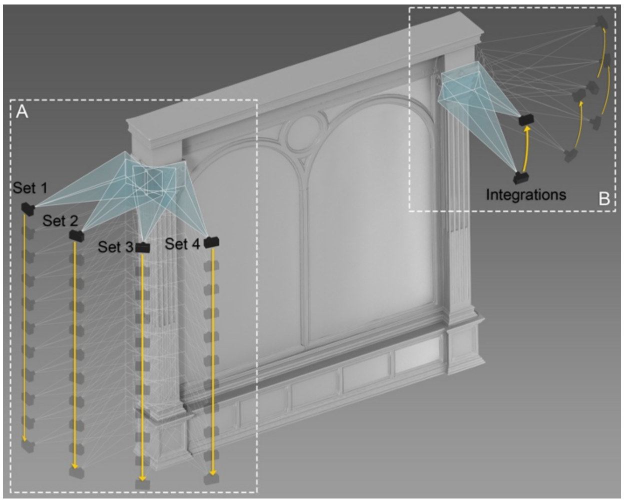

Figure 10. Network scheme for corner pilasters: A) vertical sequences (44 frames), B) integrations (8 frames) with ±20° tilt.

5.3 Workflow

The photogrammetric pipeline was performed in a six steps process:

1. RAW images conversion and color correction,
2. Cameras internal and external orientation,
3. Mesh reconstruction from depth maps,
4. Texture map building,
5. Shadows removal,
6. 3D model scaling using the Faro Focus X 130 laser scanner.

The first step follows the procedure described in the par. 4.3.1, the step 2, 3, 4 were managed using Agisoft Metashape version 1.8.3, using the 'high' quality setting to generate the mesh from depth (image size downscaled by factor of 4, i.e., GSD = 56 µm/pixel above the required resolution of 100 µm/pixel) together with the Lempitsky & Ivanov (2007) technique for texture mapping. The mean reprojection error after the Bundle Adjustment was 1,18 pixels.

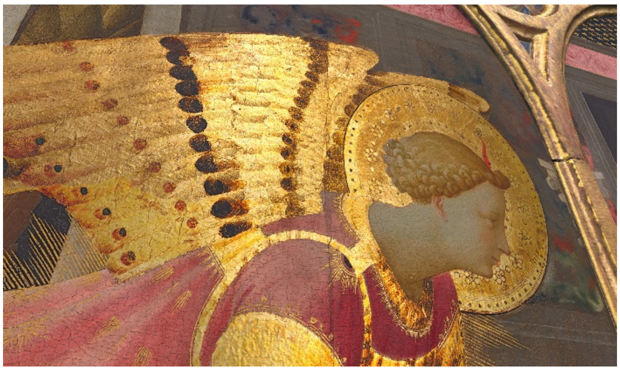

Figure 11. Gold foil 3D model visualization.

6. CONCLUSIONS AND RESULTS

The acquisition of the Annunciation aimed to develop a feasible workflow to get a three-dimensional photorealistic replica going beyond the limits of the usual two-dimensional techniques such as Gigapixel imaging, which can be accurate in resolution, but limited to a simple reproduction of apparent color, and without any ability to show the three-dimensionality of the painting and its reflection properties (Figure 11). The combination of the methods to properly replicate the painting produced a final output able to document not only the morphology but also those complex specular reflectance components and the sub-surface reflection phenomena that completely modify the perception of a such important graphic work, especially in materials highlighting at certain angles of observation (Figure 12).

Figure 12. Adam and Eve banished from the earthly paradise 3D model visualization.

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