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Artworks at our fingertips: a solution starting from the digital replication experience of the *Annunciation* in San Giovanni Valdarno

Abstract: The *Annunciation* is a remarkable artwork painted in the early 1430s by the Dominican friar Giovanni da Fiesole, better known as Beato Angelico, and now preserved at the Museum of the Basilica of Santa Maria delle Grazie in San Giovanni Valdarno, Italy. It is a wide tempera painting with some fine gold foil placed on a wooden support, representing many symbolic details hard to be fully appreciated at a distance by the observer. To enhance the museum's visitor experience on it, as well as providing scholars with a tool to help deep investigations, a digital high-resolution Digital Twin of the painting was developed. This paper summarizes the outcomes of the process, introducing the custom software applications and hardware solutions that were customized for the artwork's digital replication. Exploiting digital photogrammetry and photometric stereo techniques, the model was prepared to host colorimetrically corrected maps at Gigapixel resolution, reaching a high-definition measurable detail threshold and following a well-established process refined over time by the authors. The fruition of such a complex model was performed through a custom process ending in *AnnunciatiOn App*, a solution integrated by both graphical and physical touch interfaces, whose features grant a deep interaction with the Digital Twin on kiosks destined to exhibitions. The results feed the discussion on the production and communication of digital replicas of artworks in museum collections and how they can be upscaled to be targeted to simple visitors as well as scholars and restorers.

Keywords: Beato Angelico, 3D models of artworks, Digital photogrammetry, Photometric stereo, Gigapixel imaging, Real-Time Rendering, Haptic interaction.

1. Introduction

The Annunciation, preserved at the Museum of the Basilica of Santa Maria delle Grazie in San Giovanni Valdarno, Italy, historically comes from the nearby monastery of San Francesco in Montecarlo. Dated back to 1430-32, it represents the scene narrated by the evangelist Luke, in which the Archangel Gabriel is depicted in the act to foretell to the Virgin Mary that she would become the mother of Christ (Figure 1). This is one of the three panels with the same subject painted by the Dominican friar Giovanni da Fiesole, better known as Beato Angelico. The others are currently housed at the Prado Museum in Madrid (originally placed at San Domenico's convent in Fiesole and most likely the first authored [Beato Angelico, *Annunciation* in Madrid; Strehlke, 2019]), and at the Diocesan Museum of Cortona (originally located in the church of San Domenico [Beato Angelico, *Annunciation* in Cortona], presumably the third produced by the artist).

The painting is 2380 mm x 2340 mm wide, and it consists of two parts: the main *Annunciation* in the upper portion with the main scene with a roundel depicting the prophet Isaiah and, in the

lower side, the *predella* depicting scenes from the life of Mary. The *Annunciation* was a beloved theme in Florentine painting, and Beato Angelico contributed to nurturing this tradition. However, he adopted a more modern design and unified compositions, portraying the Virgin seated in an open colonnaded *loggia* within a fenced garden (the *hortus conclusus*). This was done to impart proportion and measurability to the painting, ultimately encouraging the viewer to draw comparisons with the surrounding environment, a landscape achieved by incorporating elements of Brunelleschi's architecture. Giovanni da Fiesole faced the challenge of harmonizing the emerging Renaissance principles - such as perspective construction and a focus on the proportions of the human figure - with the enduring medieval values of the didactic function of art with the mystical significance of light, evident in his intense brightness that eliminates shadows. This endeavor was complemented by the application of vibrant and unconventional colors. The mastery of the egg tempera painting technique played a pivotal role in his work, enabling him to craft representations in a flawless style. He often utilized costly pigments, including lapis lazuli blue and gold leaf.



Figure 1. The *Annunciation* by Beato Angelico, at the Museum of the Basilica of Santa Maria delle Grazie in San Giovanni Valdarno, Italy.

For this kind of paintings conventional photographic reproductions along with direct observation from the approved distance within the museum, do not fully capture all the richness of the artwork nor it's possible to understand its whole complexity and beauty.

Regarding the *Annunciation*, while a 2D picture diminishes the contrast between the chromatic composition featuring vibrant tones in the garden, the angel's robe, and Mary set against the dark background, the direct view at a distance to preserve the painting hinders the visitor from discerning facial details, such as the precious veil of Mary, or the nuanced depiction of Adam and Eve in the upper left portion. Moreover, the lighting conditions in the museum environment, likely divergent from those at the altar in the Convent of San Francesco in Montecarlo during the first half of the fifteenth century, impede a true understanding of materials' perception by standardizing light and dark tones, diffusing the tempera's reflection and the specular behavior of gold leaf, while excessively illuminating or flattening with perspectives surely different from those envisioned by the Dominican friar in his times.

More in general, paintings represent complex artistic creations, whose digital replicas imply the need of a faithful reproduction of the thickness of brushstrokes (which provide insights into the techniques employed by painters), the subtle nuances of their surfaces, the presence of *craquelures* (also valuable for determining the preservation state), and the way painting materials respond to light.

To overcome these kinds of problems, beginning from 2010, our research team has developed a solution for the digitization, visualization and interaction of artworks, with the aim addressed to various stakeholders interested in different levels of observation, analysis and interaction: museum visitors, art historians, restorers, professional operators and other figures engaged in painting and ancient drawings preservation and communication activities. While the initial research was primarily focused on hand drawings by Leonardo da Vinci (with a dedicated solution named *ISLe - InSight Leonardo*) [Apollonio et al., 2019], the resulting approach demonstrated its versatility by extending its application to manuscripts as well as ancient paintings [Gaiani et al., 2022]. To fill these requirements many solutions were developed in the last twenty years, but the visualization of perceptually accurate 3D models certainly remains the potentially most result-rich approach. It enables the exploration of an artwork with unprecedented freedom, allow users to zoom in on details, alter viewing angles to observe surface behaviors under different lighting conditions, and manipulate the artifact in real-time 'as in your hand' [Apollonio et al. 2021]. The developed technique is not, as usual, a 2D reproduction, but is 3D-based, aims at the characterization of the surface through a regular and spatially referenced sampling of the artwork over its entire extension, and although based on images our solution aims to overcome the limits of the methods today used to digitize the paintings: the *Gigapixel imaging*, accurate in 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; the *photogrammetric-based 3D modeling*, accurate in metric and 3D features reproduction, and

sometimes in the color replica mainly if coupled with multispectral imaging [Remondino et al., 2011] but limited in reproducing very high resolutions and reflectance properties.

Our solution gets a colorimetric visualization and analysis with an accuracy comparable to that of the visible reflectance spectra produced by the multispectral and hyperspectral methods but with the added advantage of results achieved automatically. In fact, it is less invasive for the artwork, relying on the absence of electromagnetic radiations in the infrared (IF) wavelengths and ultraviolet (UV) wavelengths that are harmful for artworks and the acquisition time is very short (approximately about one fifth of the time required for a hyperspectral acquisition), with a limited exposure to the visible light (equivalent to 1.5 hours/exhibition at 50 lux). Other advantages over spectral techniques concern the process. The system prevents from arbitrary grouping of hyperspectral image-cube “big data”; it does not require sophisticated software and skilled operators for the handling, processing, and interpretation of large data sets acquired, and it does not present problems concerning images alignment and calibration.

On the occasion of the exhibition *Masaccio e Angelico. Dialogo sulla verità nella pittura* [Masaccio e Angelico. Dialogo sulla verità nella pittura, 2022] our solution was applied to the Annunciation preserved in San Giovanni Valdarno to produce a ‘Digital Twin’, i.e., a digital replica of the real painting allowing to enable a digital simulation of the artworks ‘as it were in our fingertips’ [Niccolucci et al., 2023].

The goal of the new application, the so-called *AnnunciatiOn App*, was to bring to a wider audience of visitors, scholars, and restorers a new tool able to foster insights and discoveries in understanding the use of painting materials, their actual consistency, and ultimately, to improve the preservation of the painting and to support restoration operations.

Basically, the *AnnunciatiOn App* aims to fill the gap between an ancient drawing (the kind of art for which the original solution, *ISLe*, was created) and a painting from the point of view of their physical properties and the solution needed to produce a faithful digital replica. Briefly, first, a painting is rarely completely flat, featuring variations ranging from 10 μm to a few millimeters, whereas a drawing has thicknesses of pen or pencil marks of about 5÷10 μm , and the roughness of the paper rarely exceeds 100 μm . In addition, the surface of a painting is generally made up of a complex stratigraphy: a support-in our case a panel, one or more layers of primer, and one or more layers of tempera, fixed by semitransparent components with protective purposes. Consequently, to faithfully replicate both the painted surface and the material properties as their real counterparts are perceived by human vision in its *total appearance* [Happa and Bashford-Rogers, 2012], all these physical properties need to be replicated. This requires:

- an accurate 3D model from an accurate sampling (almost 50 μm);
- a faithful reproduction of chromatic properties (differently from drawings where the number of materials and colors is usually very limited). This implies at minimum a colorimetric reproduction workflow capable of accurately replicating saturated colors (among which

particularly problematic is the reproduction of lapis lazuli blues) the hues and the ‘chiaroscuro’ that require the ability to replicate a rich color gamut;

- a capture and visualization solution able to fill the different dimensionality of paintings compared to ancient drawings. The latter usually vary in size between an A5 and an A3 (e.g., Leonardo da Vinci’s *Vitruvian Man* is slightly larger than an A4 sheet of paper, i.e., it is 246 x 345 mm), while the paintings commonly are much larger (e.g., the size of Beato Angelico’s *Annunciation* is 2170 x 2240 mm, i.e., an area of about 60 times as large of the *Vitruvian Man*);
- an interaction interface solution catering to the diverse categories of users.

The *Annunciation’s* Digital Twin was authored following a traditional workflow, which encompassed:

- the *acquisition*, which was particularly demanding due to the materials used in the painting, their behavior to light conditions and the dimension of the artwork;
- the *visualization*, involving the production of a complete automatic system to display with perceptual accuracy not only the 3D model but also its materials’ features;
- the *interaction system*, leading to the design of a dedicated Graphic User Interface (GUI) targeted to an environment based on gestures.

This workflow is completely based on the use of photographic images and exploit techniques largely shared by the scholars (e.g. digital photogrammetry, photometric stereo, real-time rendering, multi-texture techniques), but their organization and their application to the painting field is new, with the development of specific solutions. New software applications were developed and customized for specific tasks: image RAW conversion and color correction, normal map and specular maps extraction, image and mesh fusion, material reproduction and user interface as described in Figure 2.

In this paper, we introduce the experience with the masterpiece by Beato Angelico, providing the reader with details and explanations on:

- the software tools adopted, *AnnunciatiOn App* and its modules;
- the process for the construction of the *Annunciation’s* Digital Twin;
- the outcomes from the experience.

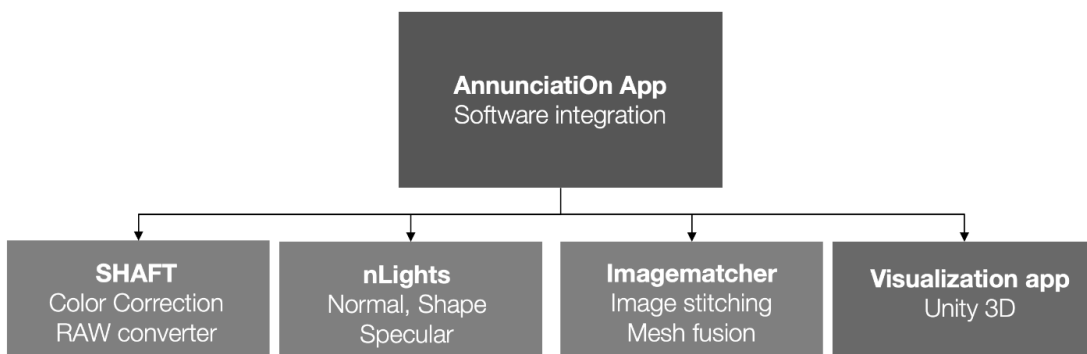


Figure 2: The *AnnunciatiOn App* as a software integration for outcomes produced by custom software solutions to acquire, visualize, and interact with artworks.

2. Material and methods

This section describes the methods and procedures created and implemented along the various stages of the digital twin's construction and use. In detail the software solutions shown in Figure 2 are illustrated. Then their use in an integrated mode in the *Annunciation* case study is described, explaining features, limitations, and ways of use.

2.1 The software tools

2.1.1 The *SHAFT* RAW converter and Color Corrector

A major problem in the digital acquisition and reproduction of artworks is the correct color and tonal establishment of the graphic work.

To fill this requirement, the most efficient and widespread solution certainly consists of reproduction using colorimetric techniques exploiting the *Five Rules of Colorimetric Imaging* expressed by Roy Berns (Berns, 2015):

- D50 workflow;
- optimal exposure;
- Color Correction (CC) based on the minimization of the CIEDE00 color difference (Sharma, 2005) with outstanding lightness accuracy;
- calibration independent validation;
- color-coding space that does not clip scene colors.

The CC of the acquired image, i.e., the image processing step (either in-camera or off-camera) that translates the color signals detected by the sensor into the corresponding pixel values, is a crucial step in this workflow.

Because the camera's sensors do not perfectly satisfy Luther's conditions - i.e., they are not a perfect linear transformation of the sensitivities of the cones contained in the retina [Jiang et al., 2013] - metamerism phenomena may occur between the camera and the eye [Lyon and Hubel, 2002], necessitating the use of CC. Therefore, the goal of CC is to modify the color measurements of the camera so that they align with color spaces that are comprehensible to the human visual system.

For digital cameras, the most common solution for achieving CC is to use tables of reference color patches with known spectral reflectance, usually measured with a spectrophotometer [Hong et al., 2001]. From their colorimetric description and the corresponding values of the acquired unprocessed pixels, it is possible to calculate the CC parameters needed to have accurate color images.

In our case the CC was fully automated through a target-based solution developed by the workgroup, called *SHAFT* (*SAT & HUE Adaptive Fine Tuning*) [Gaiani and Ballabeni, 2018].

SHAFT exploits a Calibrite ColorChecker Classic target (McCamy, 1976), it is implemented in MATLAB, and it is organized in three steps:

1. RAW image linearization;
2. Exposure equalization and white balance against the D4 patch of the ColorChecker;
3. CC in three stages: a first CC performed through a linear matrix; a per-channel polynomial fitting algorithm based on the *MATLAB Weighed Polyfit* (x,y,n) function [Gaiani et al., 2017]; finally, a procedure for successive approximations following a procedure developed by Bruce Fraser [Fraser, 2005], which involves selective variations and evaluation of the global error relative to all patches.

A crucial aspect of the CC process involves the selection of appropriate color spaces against which to apply the CC algorithms and render the final images [Süsstrunk et al., 1999]. The main parameters for choosing them are in the color gamut extension; perceptually linear encoding of the tonal scale to minimize the bit depth required to encode an image; dynamic range; illuminant white point; viewing conditions; and quantization and compression efficiency. Analysis of these parameters led to the selection of the Display P3, a 16-bit/channel color space adopted by Apple in 2015 that uses CIE D65 at 6500°K as the illuminant and a 2.2 gamma. Compared to the standard sRGB color space used as reference in most of today displays and in the Microsoft Windows OS as default color space, the Display P3 is 25% wider. Therefore, it eliminates the issues that characterize the visualization on the screens of the devices that we usually use, i.e., failure to properly display saturated colors such as cadmium yellow and cobalt blue, as well as a general shelling of all colors.

Finally, the CC process requires a validation effort, which requires the estimation of the difference between the expected color and the measured one. To establish accurate color image capture as part of the calibration function and to evaluate the deviation from the desired capture of color image information SHAFT use the most used metric, the CIEDE2000 Euclidean color difference [CIE - Commission Internationale de l'Eclairage, 2001], calculated for each color patch.

With respect to the acquisition devices employed, SHAFT yields result with color discrepancies within the 0 - 1 CIELAB unit range providing a strong basis for colorimetric reproduction of paintings.

2.1.2 *nLights* an app to reconstruct surface normal maps and geometry

The mesostructure – i.e., all those elements belonging to the surface of the painting that are still visible to the naked eye but cannot be considered as constituting its overall shape of an object as small protuberances - and part of the macrostructure – i.e., the basic geometry of the board - are rendered in *AnnunciatiOn App* by means of two bitmaps. One map simulates the normals to the surface (*normal map*), while the other simulates the depth of the surface (*height map*). The face normals play a crucial role in conveying information about surface roughness, also referred to as 3D texture or topography, implicitly simulated in the rendering replication process, while the depth evaluation allows mesoscopic deformations of the surface to be modeled.

The *photometric stereo* technique, which is based on radiometric evaluations of the photographic images, is the most appropriate and user-friendly way to extract *normal maps* and *height maps* in computer graphics [Woodham, 1980]. *Photometric stereo*, as originally defined, assumes light sources at infinity, the position of the camera orthographic to the surface to be measured, and perfectly diffuse (Lambertian) and convex (i.e., shadow-free, interreflection-free, specular-effect-free) surface behavior. *Normal map* and *height map* are then obtained by taking pictures of the surface under different lighting conditions: one image measures the diffuse reflection, while three others allow the photometric problems to be solved.

Solutions with four, five, or six light sources that could suppress maximum and minimum values and separate diffuse and specular reflections were developed over time to handle the outliers present in Woodham's original formulation due to multiple causes (self-shadowing, inter-reflections, non-Lambertian behavior, etc.) and to increase the accuracy of the results [Ackermann and Goesele, 2015].

To extract *normal maps* and *height maps* for the *Annunciation*, an application called *nLights* was created based on photometric stereo techniques. It utilizes eight images with constant illumination from four different directions, approximately orthogonal to each other and positioned at 45° and 15° relative to the painting's plane, taking advantage of a custom stand designed for this purpose (Figure 3).

Redundant conditions are used to refine the results by progressively discarding the closest values. The detection of the light direction is achieved using nine images of a chrome sphere.

Functions of the software are:

- Fitting of the circle of chrome sphere from manual extracted points;
- Finding of light directions from a given chrome sphere;
- Estimation of light strength or refinement of the lighting matrix by solving a non-linear least squares problem;
- Performing of photometric stereo to recover albedo and normal map;
- Extraction of specular reflection map from color map and albedo;
- Recovering of depth map from estimated normal vector field.

nLights is based on the MATLAB *PSBox toolbox* [Xiong, 2023] and, at the end of the process, it generates a series of maps by discarding the nearest values. These maps enable the reconstruction of the mesostructure and microstructure using multitexture techniques [Goral et al., 1984], including:

- an *albedo* map, estimating lighting matrix by solving a non-linear least square problem;
- a *normal* map, inferred by the different light directions to define the materials mesostructure;
- a *depth* map, recovered from estimated normal vector field, to define the coarse mesostructure of materials;
- a *reflection* map, to define the specular reflection of the surface.



Figure 3. The custom stand mounting the light sources positioned at 45° and 15° relative to the painting's plane.

nLights also provides a 3D geometric representation of the painting's board shape, generating meshes saved in OBJ file format, obtained from the evaluation of depth maps scaling with steel counter blocks that meet ISO 3650-DIN 861 requirements.

Using *nLights*, for each portion of the painting were extracted four different maps (albedo, gold reflection, specular and normal maps), later composed together in the rendering shader, into the visualization application (Figure 4).

2.1.3 The mosaicking in *ImageMatcher.App*

The process of combining several overlapping field-of-view photographs to produce a unified, high-resolution image is referred to as *image stitching*. The most common stitching approaches require precise image overlaps and identical exposures to produce uniform results.

This procedure that maps points from one image to corresponding points in another one is called *image registration* [Brown, 1992].

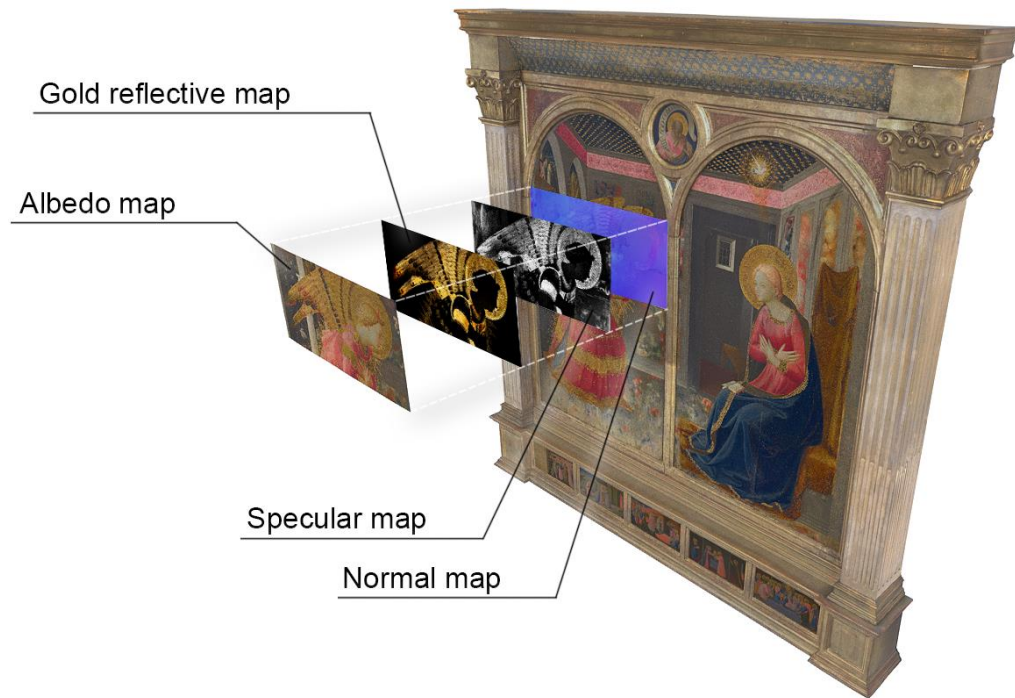


Figure 4. The different maps extracted by *nLights* for each shot, to replicate in the final shader the behavior of materials to light.

Traditionally, the image registration process follows an approach in three main steps:

- image calibration;
- image registration;
- image fusion.

Image calibration produces an estimation of the camera's intrinsic and extrinsic parameters; image registration compares multiple images to find translations for their alignment; image fusion combines the various images to create a single image.

The developed image stitching solution (*ImageMatcher.app*) follows this approach and is based on feature-based alignment [Szeliski, 2006; Nag, 2017], in which alignment is sought by matching image geometric features such as points, lines, and contours. Knowing the correspondence between several features in the images using a local descriptor [Adel et al., 2014], a transformation is determined to map the similarities between the 'target' and 'reference' images. Feature-based alignment was chosen because it offers, compared to other existing solutions, more automatic adjacency relationship (overlap) discovery between an unordered set of images, as well as faster implementation, lower computational overhead (a crucial property in the presence of gigapixel images), and increased reliability [Szeliski, 2022].

In detail, the alignment and merging of images in the *ImageMatcher.app* follows the traditional image stitching process:

1. pairwise image registration;
 - detection and description of feature points;
 - matching of identified feature points;
 - identification of the homography via M-estimator Sample Consensus (MSAC);
 - calculation of pairwise homography;
2. global alignment via Bundle Adjustment (BA);
3. image composition;
4. image merging.

The parameters extracted for color maps were later reused to stitch other maps (normals, depth, specular reflection).

To this workflow is added the alignment and merging of the meshes extracted from the *depth maps* exploiting the results of the image registration step. *ImageMatcher.app*, once the images have been acquired, then runs a 2D-3D process in three steps:

- alignment and fusion of the images;
- alignment and fusion of the meshes;
- alignment of the images to the 3D mesh.

Key features of the *ImageMatcher.app* application include:

- A. The use of a detector-descriptor operator for characteristic points consisting in a new implementation of the ASIFT (Affine SIFT) detector-descriptor [Morel and Yu, 2009], specifically adapted for images with significant rotations relative to each other [Gaiani, 2015].
- B. Approximate search for image correspondences through the organization of image descriptors into a KD-tree, using the FLANN implementation of homologous point search [Muja and Lowe, 2014], calibrated to reduce approximation in the specific case.
- C. Removal of erroneous correspondences using the robust estimator M-estimator Sample Consensus (MSAC) technique [Torr and Zisserman, 2000] more accurate of the usual Random Sample Consensus (RANSAC) solution [Fischler and Bolles, 1981]. In practice, MSAC allows to find the homography between the two images iteratively according to routine:

- random selection of four corresponding points;
- computation of the planar homography (i.e., a non-singular matrix with eight degrees of freedom) in exact form;
- computation of matches that are within a certain threshold distance of their predicted location;
- selection of the homography with the largest number of correct points;
- re-computation using all inliers of the homography that minimizes the geometric error

$$\min \sum_{\text{inliers}} d^2(x', Hx) + d^2(H^{-1}x', x)$$

where \mathbf{x} is the point in the old coordinate system, \mathbf{x}' is the corresponding point in the transformed image, H is the homography matrix, and d the displacement.

- D. Global alignment through iterative BA techniques to eliminate mis-registrations among all image pairs, achieved by minimizing the least squares errors of characteristic points' reprojection [Triggs et al., 2002]. BA was implemented using the Ceres Solver [Ceres Solver].
- E. Image blending by means of *view dependent texture mapping* techniques exploiting the camera pose of the individual images found by means of the global alignment described in the point D. The implementation done in *ImageMatcher.app* involves the selection of the best image for each triangle. This approach consists of two steps:
- Selection of the view(s) to be used as a texture for each triangle following a specific criterion (usually orthogonality between the surface and the direction of the view).
 - texture optimization to avoid visible joins between adjacent texture patches.
- The developed application performs these two operations using the solution proposed by Lempitsky and Ivanov [Lempitsky and Ivanov, 2007]:
- For the view selection, Markov Random Field optimization of the image mosaic is employed by selecting a single view for each triangle based on a graphical probability distribution model obtained by analyzing pairwise images of which view quality is judged [Li, 2009].
 - For the texture optimization, is modeled the need for leveling between texture patches between joint zones by seeking colorimetric continuity.
- F. Alignment and fusion of the meshes of individual stations obtained from the *photometric stereo* phase. Alignment is ensured by the *Iterative Closest Point (ICP)* algorithm [Bergström and Edlund, 2017] in two stages: a Fine Pairwise Registration that minimizes the alignment error between mesh pairs [Besl and McKay, 1992], and a Global Registration that distributes the residual error between all pairs evenly across all pairs of interval maps (global error minimization). Fusion is accomplished with a volumetric technique based on the well-known Marching Cubes algorithm for fusion [Curless and Levoy, 1996], which is computationally expensive but insensitive to residual inaccuracies from the previous alignment.
- G. Alignment of the images to the 3D mesh, a typical image-to-geometry registration problem [Pintus et al., 2017], performed using a statistical registration method based on mutual 2D/3D information (*Mutual Information*) as in [Corsini et al., 2009]. Figure 5 graphically shows how the alignment of the texture to the mesh is done.

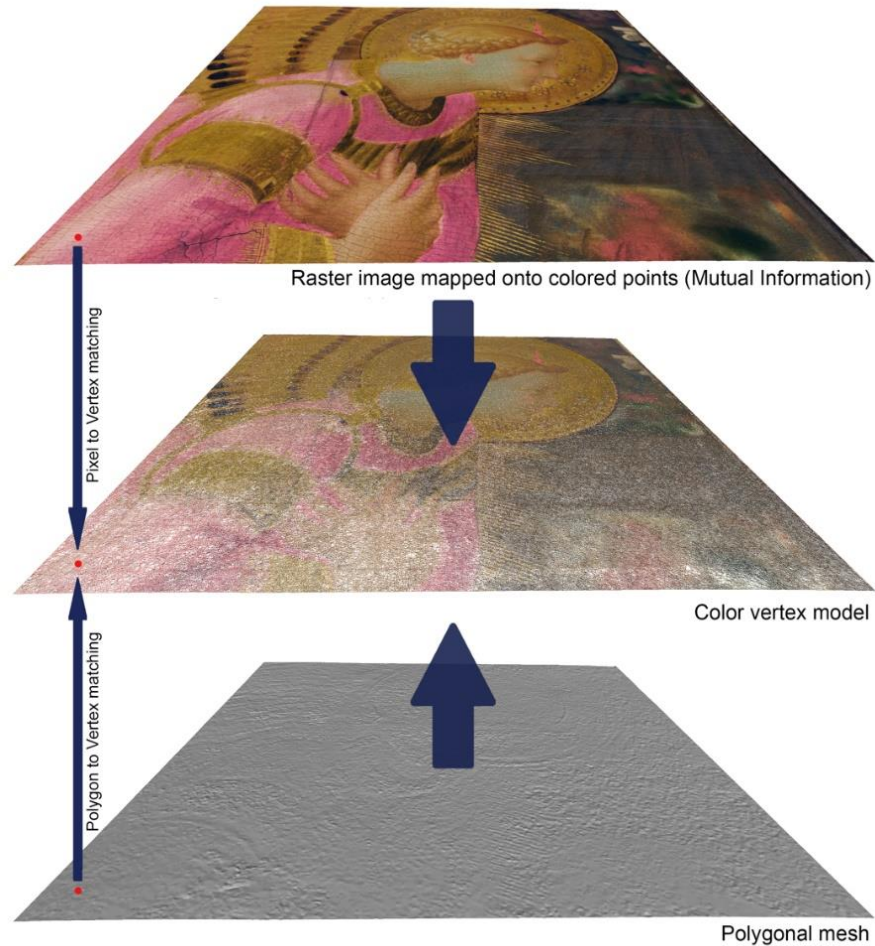


Figure 5. The principle behind the alignment of texture maps to the geometric 3D mesh.

2.1.4 The *Visualization App*

The developed *Visualization App* aims to follow this path by showing in perceptual form the three-dimensionality of the paintings and their *total appearance*, i.e., the surface reflectance and micro-geometry properties of the canvas or board and the painter's intervention. More precisely, the *Visualization App* faithfully reproduces the drawing's reflectance properties, using a process that covers three main areas [Greenberg, 2009]: goniometric (validation of the surface properties, i.e., their *Bidirectional Reflectance Distribution Function* (BRDF) [Nicodemus, 1965; Guarnera et al., 2016; Nam et al., 2018], radiometric (accurate simulation of light transport), and perceptual (final image corrected for the human eye).

Radiometric and perceptual fidelities were ensured by the development of custom-made render sequences into the *High-Definition Render Pipeline* (HDRP), a rendering framework tailored on scripts and easily customizable on top of the Unity 3D RTR graphic engine [Unity 3D engine]. It guarantees multiscale dynamic visualization with high fidelity, a general-purpose approach

that can accommodate a range of hardware platforms, and the ability to provide various levels of visualization, from those required for researchers to those for museum visitors.

Correct restitution of the BRDF (which is the core of the solution) involved the development of techniques concerning the color definition and the modeling of the surface reflectance, which play a key role in the perception of figuration.

Basically, principles inferred by the *Physically Based Rendering* (PBR) techniques were applied, i.e., scripted shaders to represent complex micro-faceted models in which glazing angles and backscattering issues deeply influence resulting spectral behaviors).

In practice, each material was described exploiting the Torrance-Sparrow theory for off-specular reflections on micro faceted surfaces [Torrance and Sparrow, 1967] as modified by Burley [Burley, 2012].

This implementation prioritizes reproduction accuracy over analytical fidelity of the physical model and allow to visually accurately mimic the different materials simply enabling the parameters and introducing the right values of the coefficients characterizing the material.

The shader including the mentioned approach was written in the HDRP Unity 3D, starting from what is reported in Doppioslash [Doppioslash, 2018]. This formulation made it possible to accurately reconstruct the reflection effects present in the many details in the painting, such as halos for the Virgin, the Archangel and many other figures represented, feature gold leaf layers presenting a metallic behavior, that reflect the energy differently from the painted surface.

Since the Gigapixel maps of a painting require huge amount of hardware resources to be displayed, they were later draped upon the 3D meshes exploiting multiresolution techniques. To avoid transition faults from one resolution to the other, a trilinear fading filter was applied in the visualizer at GPU level (results in Figure 6).

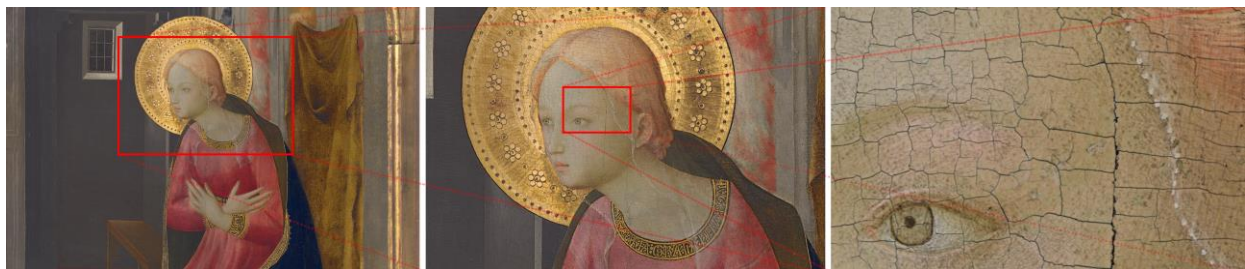


Figure 6. The seamless transition to different resolution zooming the 3D model in Unity 3D.

2.2 The reconstruction of the *Annunciation*

In this section we describe the acquisition stage to produce the Digital Twin, both for the painting and for the wooden frame. Then a description of the interaction with the rendered 3D model and the visualization environment through a software and a hardware interface is presented.

2.2.1 The acquisition of the artwork

The 3D reconstruction of the *Annunciation* is based on a method combining digital photogrammetry for the wooden frame and *photometric stereo* for the painted panels. This allows to exploit the best characteristics of each of the two techniques. In Figure 7 the two portions of the model are represented, to specify where the different techniques were used.

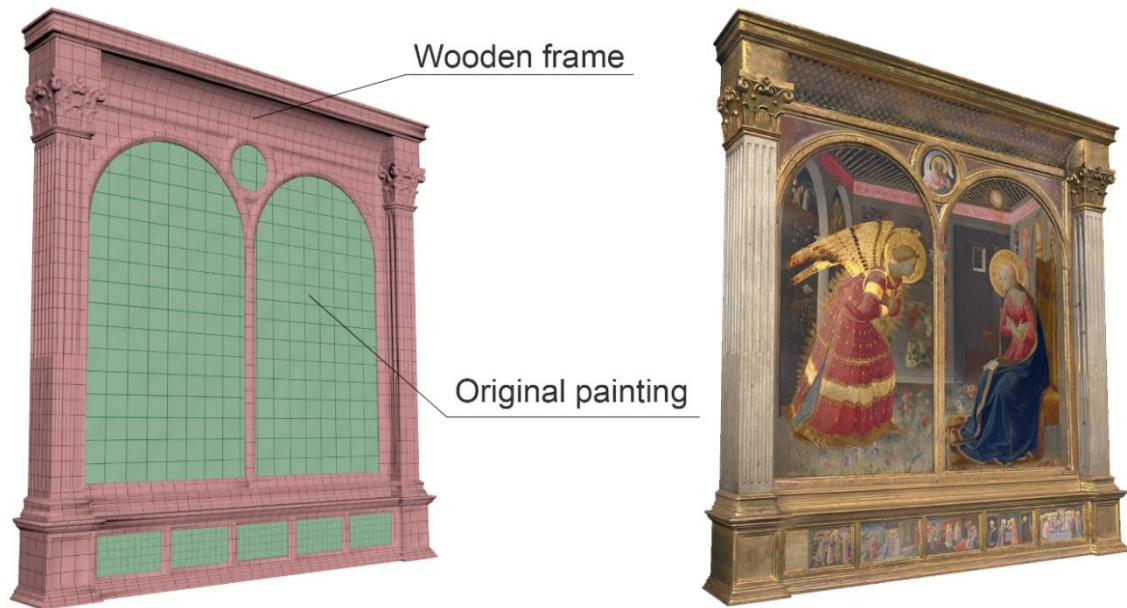


Figure 7. The two portions of the *Annunciation*: the original painting, acquired with photometric stereo, and the wooden frame, acquired with photogrammetry.

The acquisition of the painting

The painting was acquired exploiting the combined use of photometric stereo and Gigapixel imaging through the software applications *nLights* and *ImageMatcher.App*.

The images of the painting were taken using a Hasselblad H6D-400C Multi-Shot medium format camera, equipped with a 53.4x40 mm Sony CMOS sensor with 4.6 μm pixel pitch, for a maximum resolution of 23200 x 17400 pixels (through 6 shots) with non-interpolated 48-bit color depth. The Multi-Shot technology, which the camera features, 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 automatic shots taken by moving the sensor by half a pixel at a time. As lens was used a 120 mm Hasselblad macro lens.

For the acquisition a custom repro stand was built [Bacci et al., 2023] able to host the camera and the thirty-two light sources (eight per side, in groups of four inclined at two different angles, 15° and 45° relative to the acquisition surface) presenting the following features:

- a stable structure to minimize blurring caused by oscillations and vibrations and small movements of lamps that may cause potential non-uniformity of the light set;

- both vertical and horizontal mobility for effective mosaicking, because of the painting's size and the restricted frame of each picture taken to achieve the required resolution.
- safety management of distance and parallelism to the plane of the painting;
- lighting system positioned on all four sides, equidistant from the center of the acquisition area to guarantee homogeneous illumination;
- no interference between the light sources and the camera;
- a separate structure aimed at the calibration procedures (Figure 3).

The adopted approach aligns with that proposed by Pedro M. Cabezos-Bernal [Pedro M. Cabezos-Bernal et al., 2021] to prevent from blurry shots and radial distortions issues from the lenses. It keeps the camera parallel to the painting and the lighting system fixed with it. This ensures a constant distance between the sensor and points on the painting, maintaining optimal sharpness of the images without being constrained by the depth of field. Additionally, the reflected light from the artwork remains consistent across shots, preventing slight exposure differences and issues with specular reflections.

In Figure 8 is represented the shooting plan, designed considering the covered area for each shot equal to 500×375 mm with camera sensor constrained at 1120 mm from the painted surface, and a minimum overlap of approximately 25% between adjacent frames, to later achieve high-quality stitching, and a Ground Sampling Distance (GSD) equal to $21 \mu\text{m}/\text{pixel}$.

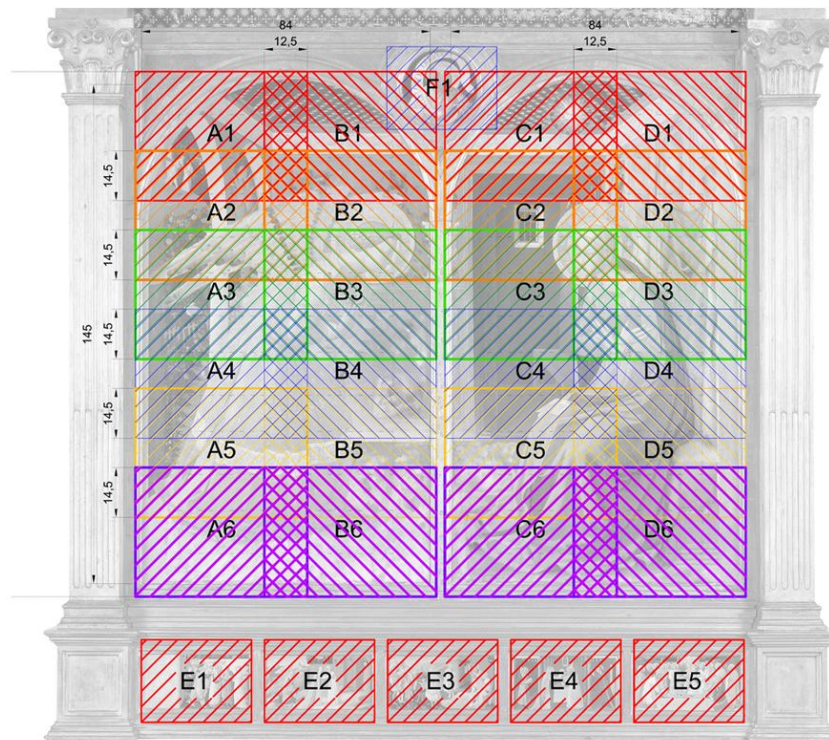


Figure 8. The overlapping plan designed for the acquisition stage, considering a minimum overlap among shots of approximately 25%.

The acquisition of the wooden frame

The wooden frame was acquired exploiting the digital photogrammetry using a full-frame Canon EOS 5D Mark III with Canon EF 100 mm f/2.8 Macro USM lens with a circular polarizer filter applied, with the aim to attenuate specular reflections. A remote controller was used to avoid blurring and micro-blurring effects due to human interaction.

A comparison chart for the technical specifications of the two cameras used during the whole acquisition (both for the painting and its wooden frame) are detailed in Table 1.

Table 1. Camera devices used in the digital acquisition of the *Annunciation*.

	Hasselblad H6D-400C (Multishot - Painting)	Canon EOS 5D Mark III (Wooden frame)
Sensor name	Sony	Sony
Sensor type	CMOS	CMOS
Sensor diagonal (mm)	66.64 mm	43.27
Sensor Size	53.4 × 40.0 mm	36 × 24 mm Full Frame
Image resolution	11600 × 8700 px	5760 × 3840 px
Pixel size	4.6 μm	6.25 μm
Focal length	120 mm	100 mm

To fulfill the condition to have a minimal resolution of 50 μm/pixel the camera distance to the canvas was fixed to 700 mm allowing a Ground Sampling Distance (GSD) equal to 28 μm/pixel.

Three different kinds of issues were addressed:

- the frame's shape which cannot be approximated to a like-planar object.
- the high specular reflections of the frame, especially in gold foil areas as their appearance changes with the change in the illumination direction (Arteaga et al., 2022).
- the asymmetric lighting system in the museum room where the artwork is located that cannot be turned off or dimmed.

The acquisition scheme was designed considering the camera's optical axis as perpendicular to the average vertical plane of the artefact (Figure 9), to prevent from blurry shots and radial distortions issues from the lenses [Cabezos-Bernal et al., 2021], using a regular pattern (with equal spacing). Then other additional pictures were taken for the lower *predella*, for each pilaster and for the upper frame. Further details can be found in [Fantini et al., 2023]. Shadows on the images were removed using a simplified 3D reconstruction of the actual layout at the museum, as detailed in [Apollonio et al., 2023].

Before the final alignment, parts were scaled considering a series of measurements coming from the Faro Focus 3D X130 laser scanner. It has a lateral resolution of 2 mm at 10 m and a depth measurement uncertainty of 0.15 mm.

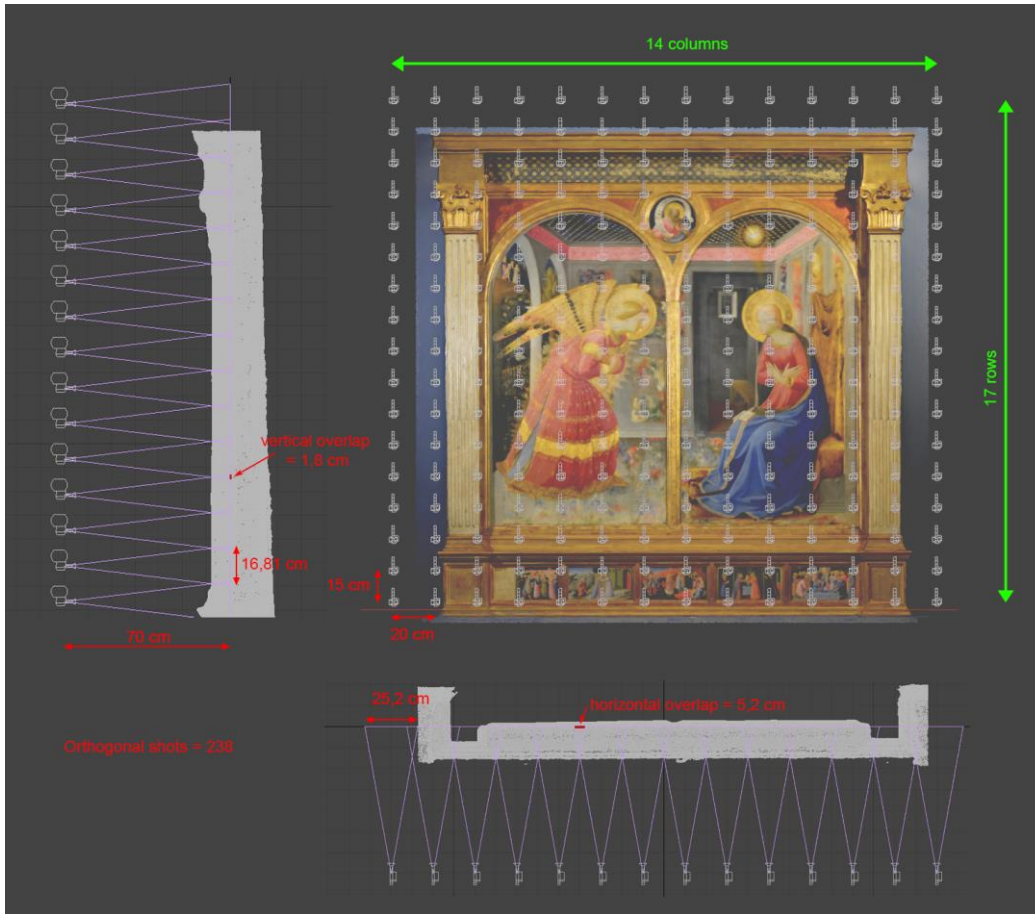


Figure 9. The camera network for the photogrammetric acquisition (image courtesy of Filippo Fantini).

2.3 The hardware and software interaction system

To allow the visitors of Museum of the Basilica of Santa Maria delle Grazie to interact and to enhance the *Annunciazione* experience, the *AnnunciatioOn App* was placed near the original painting in a kiosk made of wood, to recall the frame around the original artwork (Figure 10). The vertical wooden structure was conceived to host a touch screen and to hold all the necessary hardware to run the app, including a workstation hidden behind a panel that can be removed to guarantee maintenance operations. Shape and dimensions of the whole case (110 x 220 x 49 cm) and its single parts were sized starting from ergonomic considerations.

Paintings are complicated works of art, therefore exploring 3D models just with touch monitors might be restricting. Furthermore, the relationships between an information model and its end user are complex since data must be conveyed as effectively as feasible.

To facilitate interactions both a software system, including a Graphic User Interface (GUI) in the visualization app, and a hardware soft-touch keyboard, were designed. This made it possible to provide a hierarchical organization to the information to easily display it.

The decision to split interaction processes into two separate levels, one physical and the other digital, aims to develop an information architecture model suitable for interaction in a traditional museum space. Contemporary studies show that simplifying interaction processes using physical activators helps visitors initiate initial interaction with the artifact (Petrelli et al., 2014). The developed system combined capacitive technology with a backlit plexiglass element. Once a specific section was selected through a touch on the physical button, the digital content was activated on the screen, enabling the visitor to consult more specific content in detail. In this way, a great variety of notions, anecdotes, technical information, and art-historical details are transferred to the user in the museum, who can observe the original work with greater awareness, once he explores the Digital Twin.

The narrative part is at the lowest level of the hierarchy and covers specific aspects related to the five themes addressed: the *Annunciation* painting, the *predella* paintings, The House and Garden, the technical analyses carried out over time, and the comparisons with the other “*Annunciations*” by Beato Angelico.



Figure 10. The *Annunciation* by Beato Angelico at the Museum of the Basilica of Santa Maria delle Grazie in San Giovanni Valdarno. The kiosk application running *AnnunciatiOn App* is placed close to the real artifact, on the left.

As each section gathers further information nested within its respective theme, a hardware interface has been created to allow for a friendly first approach to the app. This interface allows the user to select the section of interest with immediacy, by touching a simple 5 buttons keyboard. Once activated, the details grouped in the section can be viewed on the screen, where the software interface allows for more in-depth interaction, showing exploration icons.

2.3.1 The Graphic User Interface

Since the monitor in the kiosk installation is hosted vertically, GUI was designed with 9:16 proportions optimized to run on a 55" touchscreen at 3840 x 2160 pixels resolution. The vertical 3D model visualization is flanked by buttons overlaid on a touch screen area made of semi-transparent circles in the size of a finger. Using them users may navigate the model, moving back-and-forth to specific details on the painting, with commentaries grouped into five sections of interest. Table 2 lists the contents introduced and their belonging sections.

Table 2. Captioned sections in which views are organized in the interactive interface.

Section ID	Section name	Contents
Section A	The <i>Annunciation</i>	The painter: Fra Angelico - The location: Montecarlo - The painting during World War II - The subject: The Annunciation - The Dove - The Virgin - The Virgin's book - The Prophet - Adam and Eve.
Section B	The <i>predella</i>	Predella - Scene 1: The Marriage of the Virgin - Scene 2: The Visitation - Scene 3: The Adoration of the Magi - Scene 4: Presentation of Jesus in the Temple - Scene 5: Burial of the Virgin.
Section C	The House and Garden	The <i>hortus Conclusus</i> - The rose - The lily - The palm - The loggia - Pentimenti in the arches - The Interior Room - The Flowers.
Section D	Technical Analysis	The wooden support – UVs - Infra-red reflectography – Lapis lazuli - Other Pigments – Gold.
Section E	Other Annunciations	The other Annunciation altarpieces - Museo Nacional del Prado, Madrid - Museo Diocesano, Cortona - Comparison of the Virgin's house in each altarpiece - Comparison of Adam and Eve in each altarpiece - Comparison of the Visitation Scene in each predella.

A 'home' button initiates the exploration from the starting point, while a 'world icon' triggers an automated tour following a predetermined path. Users can also systematically navigate through all guided details using two 'arrow' icons.

The comparison between the real *Annunciation* and the one replicated in *AnnunciatiOn App* proved to be particularly effective, since visitors can get in touch with the masterpiece in a personal way, 'touching' its virtual replica to establish a more intimate relationship with the artefact.

The robustness of the touch interaction system is guaranteed by customized routines written to avoid multiple buttons selections or to program the application to restart from the beginning if no activity is detected within a timed interval.

2.3.2 The physical interactive controller

A physical proximity interactive controller was placed below the vertical screen to give users an easy and direct access to each one of the thematic sections. By barely touching the keyboard, which consists of five palm-sized buttons, the reference section is shown on the screen.

This physical interface was developed through the adaptation of a dedicated Arduino board based on a ATmega32u4 microcontroller (Leonardo type), which drives the capacitive touch buttons illuminating them to visually indicate the selected section through a flashing white light.

Each single button was made of a 3D printed ring, made of white Polylactic Acid (PLA), around which was placed a NeoPixel strip with 5 RGB WS2812 LED diodes, to illuminate a transparent methacrylate disc and diffuse light. Below, a vetronite plate, a material often used for circuits boards, is used as capacitive surfaces and was soldered to two pins in the electronic controller to transform them into sensors able to perceive the electrical capacity of human hands.

The buttons act as antennas and, through a correct calibration, it was possible to interact with the model when the hand was in the proximity of each circular element.

The choice to use a capacitive button instead of a mechanical solution is tied to the need to ensure system efficiency in relation to the high number of visitors who could have used the product over the years. A touch solution does not experience material degradation because it is not subject to mechanical stress.

In Figure 11 the physical keyboard equipped with the capacitive soft buttons is illustrated.

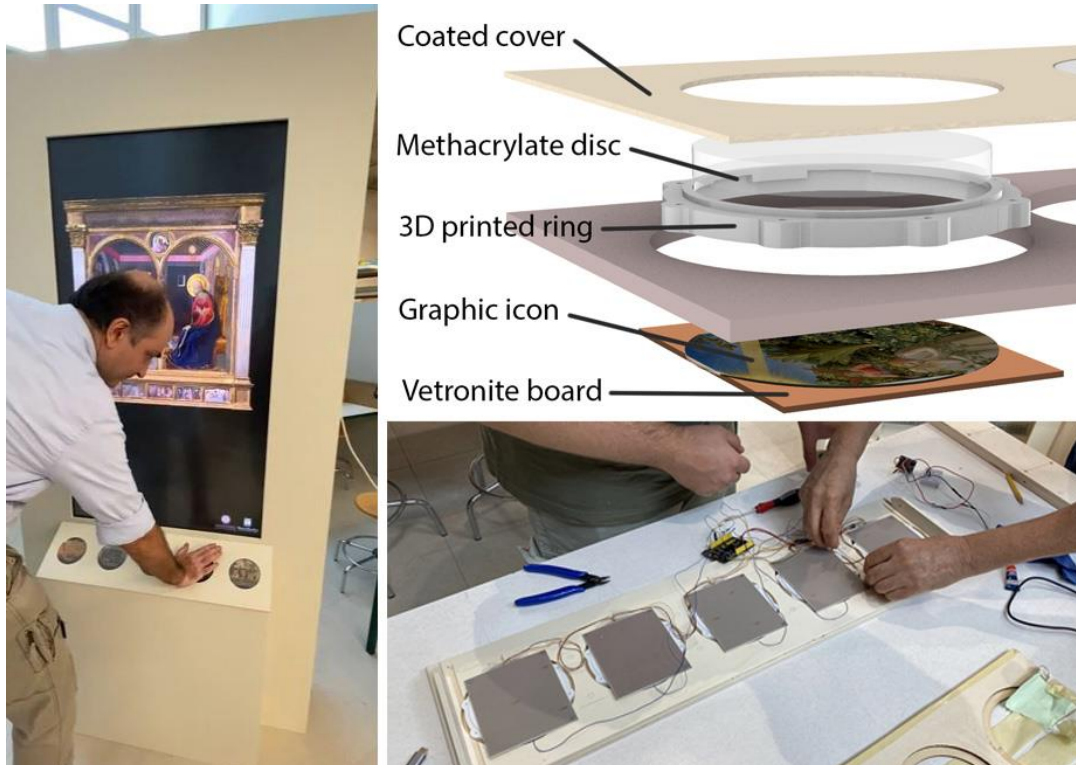


Figure 11. The physical touch keyboard with the five methacrylate discs leading to the five semantic sections of the guided kiosk tour.

3. Results

To present the accuracy and the performances of the proposed image-based methods for the painting panels four outcomes were introduced:

- features of the high-resolution maps
- color fidelity
- effective resolution
- visualization results.

3.1. The features of the high-resolution maps

Almost 270 pictures were acquired with the Hasselblad camera. Overall, the whole picture dataset acquired files totaled approximately 106 Gigapixels, corresponding to 26.9 Gigapixels after their fusion in mosaicked maps (Figure 12). The grand total in the output resolution includes the four maps produced for each part of the painting (Table 3). The reprojection error from the alignment for the two panels after the BA is approximately 0.68 pixels.

Table 3. Number and dimension of the textures mosaicked after the stitching in *ImageMatcher.app*.

Painting's part	Mosaicked portions	Overlaid maps	Dimension of the single map (pixel)	Resulting dimension of each mosaicked map (pixel)	Resulting dimension in Gigapixel (including the 4 maps)
Upper roundel	1	4	11125x11125	11125x11125	495 Mp
Left panel	12	4	20180x17980	40360x71920	11,6 Gp
Right panel	12	4	20240x17990	40480x71960	11,6 Gp
Predella	5	4	18275x8825	18275x8825x5	3,2 Gp
					26.9 Gp



Figure 12. The resulting mosaicked maps (from the left albedo, reflectivity, specular and normal maps).

3.2 Color fidelity

Color accuracy after CC was assessed according to the following parameters:

- mean and maximum color difference relative to the mean ideal chroma in the CIEDE00 color metric on the CIEXYZ chromaticity diagram;
- mean of absolute luminance; exposure error in f-stops measured by pixel levels of patches B4-E4, using gamma values measured rather than the standard value for the color space (i.e., in the case of Display P3 with gamma 2.2).

As reference for the CIEDE00 mean, values less than 1 are appropriate; for DL mean values less than 1 are required; for the exposure values less than 0.1 f-stops are needed.

General results are illustrated in Table 4. In Figure 13 is represented an example of the visual results of the CC process.

Table 4. Color accuracy measured with the CIEDE00 formula, using a Calibrite ColorChecker Classic.

CIEDE00	DL	Exposure error
CIEDE00 mean = 0.85	DL mean = 0.18	0.00 f-stops

3.2 Effective resolution

The solution adopted to measure detail preservation was the evaluation of the *Modulation Transfer Function* (MTF), a value expressing how accurately an imaging device or system can reproduce a scene. The MTF quantifies the degree of attenuation with which the whole system reproduces variations in luminous intensity based on its spatial frequency. It is standardized in the ISO 12233 and its 2000 version was used [Parulski et al., 2022].



Figure 13. Comparison of the same shot as it was taken by the camera and exported from the raw file format (a) and the color corrected result following the process developed by the research group (b).

Since 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, the MTF was measured at two different spatial frequencies to preserve pixel density and to determine how accurately our imaging device could reproduce the painting [Jacobson, 1995; Burns, 2000]:

- the MTF10, an indicator of the maximum resolution though influenced by image sharpness;
- the MTF50, an indicator of the sharpness of cameras and lenses, were measured before the acquisition of the painting.

The combination of camera, lights, and the custom stand led to an average spatial resolution with the rising edge distance (10-90%) equal to 11.47 pixel. The values for the resulting MTF 50 and MTF 10 were respectively estimated in 0.133, and 0.256 line pairs/pixel (Figure 14).

The effective resolution (GSD), after restoring the sensor and lens blur through an Unsharp Mask filter off-camera [Burger and Burge, 2009], was confirmed in 21 μm .

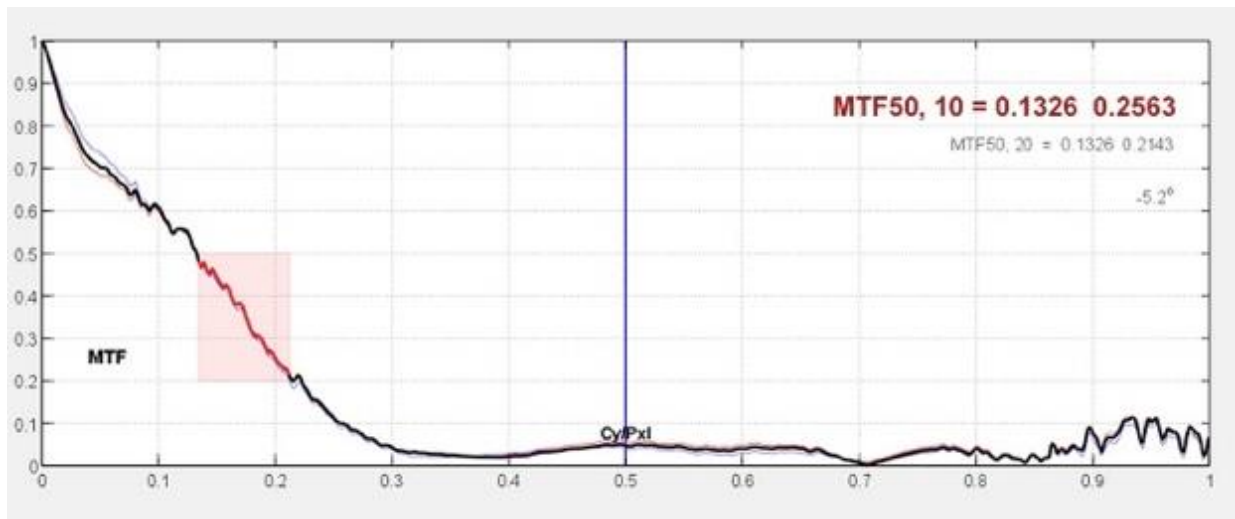


Figure 14. The graphic trend of MTF values as resulting from the estimation.

3.4 The visualization results

Visual results of the graphic rendition of the Digital Twin and its level of detail are presented in Figures 15 and 16.

Figure 17 shows the visualization GUI in kiosk mode, with the touch buttons in the lower right part of the screen and the changing captions aside.



Figure 15. The visualization of the *Annunciation's* Digital Twin: results in displaying small details and the archangel with the gold-foiled wings.



Figure 16. Results in displaying some painted details in the *predella*.

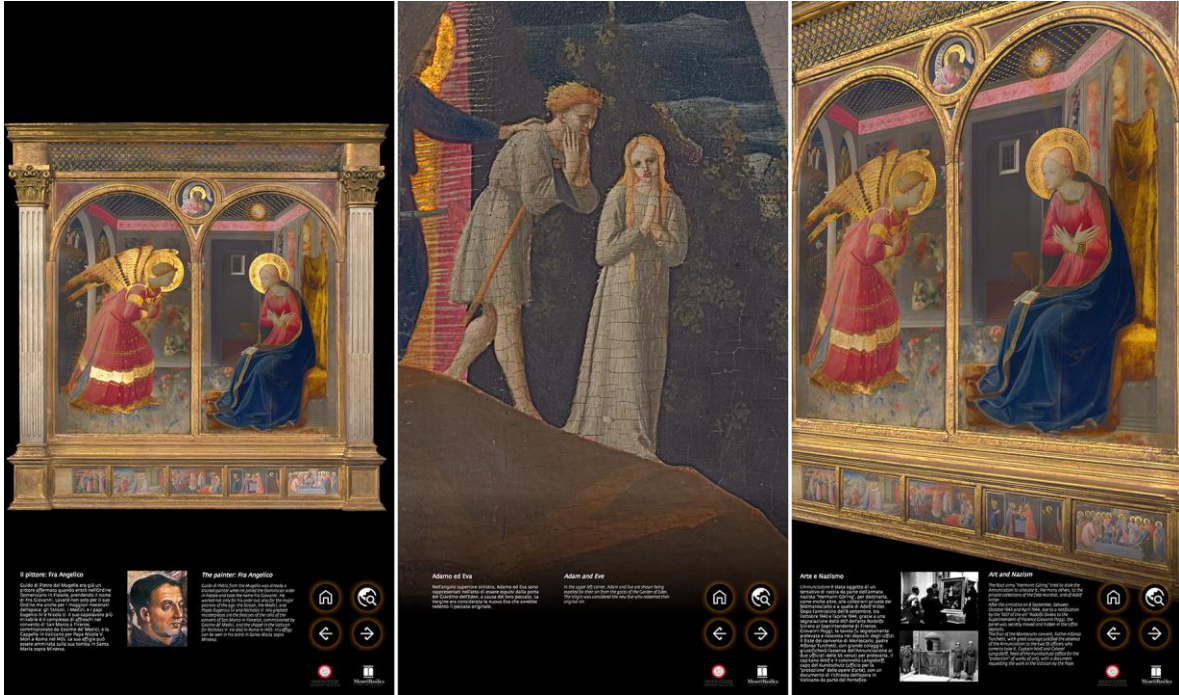


Figure 17. Details can be explored touching GUI's arrows with texts and graphics will pop up accordingly.

4. Conclusion

The creation of software and hardware solutions to allow a better comprehension of artworks, new knowledge, new insights about them, and an easier communication of their contents is today crucial for museum institutions aiming to effectively compete with leading players in the field [Marani et al., 2022].

The key to enabling this agenda is to have a less 'cumbersome' and more efficient process to digitize, visualize, and interact with artworks than those used by major museums, as well as less economic efforts and high-fidelity digital representations (i.e., Digital Twins) of the originals as output. The goal is providing a wide range of users with high-res reproductions readily available for the study and communication of the original artefacts they mimic.

In this paper we introduced the experience of the acquisition, visualization, and interaction with the digital replica of the *Annunciation* by Beato Angelico and the related application and hardware solutions developed and grouped in the *AnnunciatiOn App*, a complete software ecosystem that integrates different applications (Figure 18). Offering an internal solution to get high-resolution 3D models more swiftly, in contrast to the extended timelines of other projects in literature, *AnnunciatiOn App* presents a strategic advantage by leveraging the expertise accumulated by the research team over the years and the creation of output address to both museums' users and CH professional operators and scholars.



Figure 18. The *AnnunciatiOn App*, integration of different solutions and targeted to different final users to let them better understand and enjoy the work of art.

The realization of the Digital Twin of the *Annunciation* was the result of mostly a multidisciplinary approach, since the iterative construction of the process behind the *AnnunciatiOn App* underwent through collaboration with art experts, and restorers, whose knowledge was fundamental to highlight the most important features of the painting and communicate it through captions or comparative images to be displayed together with the 3D model. The earlier works on drawings by Leonardo helped identify both strengths and weaknesses.

Presently, continuous refinements and improvements are actively underway to further improve and optimize the application's capabilities and the whole process to generate it, allowing scholars to better understand and transfer complex information to visitors in a way easy to understand. Due to this reason, the different options in which a digital model can be explored represent a future perspective, bringing into the discussion the potential of information collected in virtual representations of art.

Specifically, the creation of the digital replica of Beato Angelico's *Annunciation* in San Giovanni Valdarno aligns with the discourse on the features of architectural survey discipline, even though it involves the study of a painting.

This remark is primarily motivated by intrinsic features of its representation, since it is like a microarchitecture, and its deep connection with the cultural environment in which it was created, involving notable figures such as Lorenzo Ghiberti, Filippo Brunelleschi, and Leon Battista Alberti. These connections also influenced the new architecture of the time, shaping its setting and context [Mozo, 2019].

However, the fundamental connection lies in the method employed to approach this microarchitecture. Simple measurement and drawing operations are marginal compared to the intricate knowledge demanded by the painting: complex details, color nuances, surface reflections, and evidence of issues that have surfaced over time influencing the state of preservation. Today, such knowledge is crucial in documenting historical architectural artifacts for their conservation, redesign, and planning purposes.

A replica based on a simple 2D outline, with few measurements only, offers limited cognitive and operational utility. It fails to significantly contribute to assessing the quality of materials and encrustations accumulated over the centuries. As Jean-Paul Saint Aubin explained almost a quarter of a century ago, a survey is a *“comprehensive tool that seeks to depict the actual form of a construction, including its deficiencies, irregularities, and transformations over its history. It serves as an educational instrument, aiming to facilitate understanding of the work's operation within the complexity of its history, analyze the models it references, and identify the innovations it introduces. Additionally, it serves as a tool to assess the structural health and identify weaknesses, seeking solutions based on irrefutable documentation”* [Saint-Aubin, 1996].

The solution proposed in this paper strives to recover these often-overlooked elements, moving towards forms of knowledge that are more comprehensive and aligned with how we perceive and logically process the historical artifacts that surround us.

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