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FROM CAPTURE TO LIGHT: AN INTEGRATED PROCESS FOR THE THREE-DIMENSIONAL ACQUISITION OF PAINTINGS IN VIEW OF THEIR RE-ILLUMINATION

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Abstract

The replication of ancient paintings involves significant challenges, especially when considering that modern viewing conditions differ greatly from their original settings. This contribution presents the results of a digital acquisition campaign focusing on three historically significant paintings: two works by Ludovico Mazzolino from Le Gallerie degli Uffizi and Titian's "Portrait of Alfonso I d'Este" from Palazzo Pitti in Florence. As part of the *DarkScape Experience* (DSE) research project, this work aims to digitally reconstruct the paintings to relocate them in a virtual representation of their context at Villa d'Este, in Tivoli, to simulate original viewing conditions regarding daytime and nighttime illumination as documented in historical sources. The integrated process presented produced three-dimensional models replicating the visual aspects, the characteristics, and the materials of the real artworks, through multilayered textures and 3D meshes including both painted wood panels or canvases and their frames.

Keywords

Architectural Heritage, History and Philology of Fruition, Lighting design, Digital acquisition of painting, Virtual museums

1. *Introduction and general background*

Building on ideas first presented by Leonardo da Vinci in his *Treatise on Painting* regarding the illumination of paintings and sculptures, Sebastiano Serlio formulated his own fundamental reflection, which would have enormous resonance throughout the modern age. In his *Third Book in which the Antiquities of Rome are Illustrated and Described,* printed in Venice in 1540 with a dedication to King Francis I of France, the Bolognese architect and treatise writer argued that Venetian painting, particularly that by Titian, was well suited for nocturnal viewing, or to be viewed in the semi-darkness of candlelight; unlike Tuscan-Roman painting which instead required ideal conditions of daylight, such as those created under the oculus of the Pantheon, suitable for enhancing the grace of the figures together with the typically Florentine perfection of *chiaroscuro*.

The issue, completely neglected by modern studies, is now at the center of investigations conducted within the PRIN PNRR DarkScape Experience (DSE) Project[1]. This is a technological-scientific, educational and cultural project that aims to create three-dimensional digital reconstructions of environments belonging to historical buildings (studios, galleries, chapels) with the purpose to recreate the observation conditions of paintings as they were when the artists created them; not only in the daylight but also in the nightlight, according to the ancient methods of *dark fruition* widely attested by literary, documentary and historiographical sources. The 3D models produced from the acquisitions aim to relocate these digital replicas within their original reconstructed virtual

[1] The topic is extensively addressed by Carmelo Occhipinti in the chapters of a forthcoming book dedicated to the history of the illumination of works of art.

environments, making it possible to analyze for educational and scientific purposes both the environment itself and the individual artworks, to appreciate them according to the different lighting conditions, the material qualities, the stylistic and expressive specificities, and the ability to react to the most diverse luminous *stimuli*. To achieve its objectives, DSE integrates three different methods into one framework:

- a method for the philological reconstruction of an original context room belonging to a historic building, according to the documents on the original furnishings and light fittings;
- a method for the reconstruction of the BRDF (*Bidirectional Reflectance Distribution Function*) of the materials constituting the furnishings and interior surfaces obtained with photographic methods and their visualization within a physically based *Real-Time Rendering* engine (RTR);
- an abacus of light sources completed with their lighting characteristics for their digital visualization and possible integration into a system for the optimization and management of digital and, where they exist, real spaces.

The DSE project aims to integrate the different perspectives of digital representation experts and art historians. The former is interested in defining a method for reproducing paintings with their optical reflection properties and the lighting generated by flame sources, while the latter can study the original locations, the features of the spaces in which the paintings were placed, and the lighting conditions that illuminated the paintings.

This paper presents the method for reproducing paintings with their optical reflection properties and their placement in the reconstructed original space, in view of their virtual re-illumination with candles and torches. Specifically, the process of digitally acquiring paintings is illustrated, based on research that began in 2010. Initially, it was focused on Leonardo da Vinci's drawings, with a solution called ISLe (*InSight Leonardo*; Apollonio et al., 2019). Then, the research was extended to ancient paintings (Gaiani et al., 2024).

The approach, which relies on pictures only, differs from conventional solutions similarly based on gigapixel images, whose resolution accuracy is often counterbalanced by limits in reproducing apparent color, without capturing the three-dimensionality of the artworks and their reflectance properties - as in the remarkable Rijksmuseum's *Operation Night Watch* project (Rijks Museum, 2025) - or allowing observation only from a predefined viewpoint – as in the Dome Photography coupled with RTI techniques (Malzbender et al., 2001).

The process presented in this paper is based on a 3D characterization of the entire surface of a painting through regular and spatially referenced sampling, focusing on reproducing the optical properties of materials, such as brightness, color, gloss, and roughness, to prepare simulations suitable for visualizations under different lights.

2. *The digitized artworks*

In 1536, the Cardinal of Ferrara Ippolito II d'Este could display several works of art in the "*Camerino*" [*small chamber*] of the palace that Serlio built for him at Fontainebleau. Some years later, many of these artworks were exhibited in the "*camerino*" on the upper floor of his palace in Tivoli. These Venetian and Ferrarese paintings were well-suited for nocturnal viewing by lamp light, according to various historical testimonies (letters, inventories, expense records) on which the project to virtually restore the original lighting conditions, common in the 16th century but quite different from those to which current museum lighting systems have accustomed us, is based.

Among other artworks, three paintings were digitally acquired for light simulations, with the outcomes presented in this paper:

- *Strage degli Innocenti* [*Massacre of the Innocents*] (Inv. 1890-1350, 720 × 525 mm. with frame), oil on wood panel hosted at Le Gallerie degli Uffizi in Florence;
- *Circoncisione di Gesù* [*Circumcisium*] (Inv. 1890-1355, 440 × 540 mm. with frame), oil on wood panel hosted at Le Gallerie degli Uffizi in Florence, both by Ludovico Mazzolino;
- *Portrait of Alfonso I d'Este* (Inv. 1912-311, 1230 × 1540 mm. with frame), by Tiziano Vecellio, oil on canvas hosted at Palazzo Pitti (Galleria Palatina e Appartamenti Reali) in Florence.

Furthermore, 3D models of two additional paintings, nevertheless not addressed in this work, were produced to complete the set of artworks to relight:

- *Portrait of a Young Woman known as "La Bella"* (Inv. 310-1959.2, 950 × 800 mm.), by Jacopo Palma the Elder, hosted at Thyssen-Bornemisza Museum in Madrid;

Fig. 1: The 3D model of the *Massacre of the Innocents,* by Ludovico Mazzolino.

Fig. 2: The 3D model of the *Circumcision,* by Ludovico Mazzolino.

- *The Holy Family with a Lamb* (Inv. P000296, 280 × 215 mm.), by Raffaello Sanzio, hosted at Prado Museum in Madrid.

These five paintings were originally placed in the so-called "*Fourth Camerino*" in Tivoli as they appeared in the private apartment, at the time of the death, of Cardinal Ippolito d'Este (1572).

The two small paintings by Ludovico Mazzolino depicting the *Massacre of the Innocents* (Figure 1) and the *Circumcision* (Figure 2) must have been very dear to Ippolito, who kept them with him at least since the time of his move to France. These are the paintings that the inventory "*delle gioie di Ippolito II d'Este portate in Francia [about the jewels of Ippolito II d'Este taken to France]*," October 1535, records as "*uno quadro intaiado con lo suo cimo dorato a mordente, con la Istoria deli Nocenti, fatto a olio de figurine picole [a framed painting with its crest gilded with mordant, with the Story of the Innocents, made in oil with small figures]*" and "*un altro quadro de ligname intaiado e dorato a mordente, con la Circontione [sic] de Christo de figure a olio, de figure picole, de mane de maestro Bigo Mazolino [another wooden painting framed and gilded with mordant, with the Circumcision of Christ with oil figures, of small figures, by the hand of master Bigo Mazolino*]"[2].

Through this document, it is possible to observe the formation of the first nucleus of Ippolito's collection, consisting of pieces removed from the ducal wardrobe of Ferrara.

Mazzolino, who passed away by 1530 (but had already prepared his testament in 1528 when afflicted with plague), was a well-recognized painter in the Ferrarese court.

His activity has been documented since the first decade of the sixteenth century, and the themes of the *Massacre of the Innocents* and the *Circumcision* were certainly very familiar to him, as he had addressed them multiple times in works generally destined for private devotion.

An example is the version of the *Massacre of the Innocents* currently housed at the Doria Pamphilj Gallery in Rome which alludes, in its simulated marble frieze, to a fragment of a Bacchic sarcophagus known to artists of Northern Italy since the mid-fifteenth century (Savy, 2007, p. 106).

Regarding the *Circumcision*, two other versions exist, in addition to the one being discussed here, preserved at the Kunsthistorisches Museum in Vienna and at the Cini Foundation in Venice[3].

[2] Archivio di Stato di Modena [ASMo], Camera Ducale, Amministrazione dei Principi, 924, c. 84. Occhipinti 1997, pp. 602-603, notes 5-6; Guidi 2023, pages 228-230.

[3] On the Cini *Circumcision* see E. Sambo in *Galleria di Palazzo Cini* 2016, pp. 203-205, n. 43, where it is reaffirmed, in contrast to previous interpretations based on a document published by Campori (1870, p. 37), that the *Circumcision* by Mazzolino possessed by Ippolito II is the one currently housed at the Uffizi.

Fig. 3: Copy after Titian (late 16th-early 17th century), *Portrait of Alfonso I d'Este,* New York, The Metropolitan Museum of Art (Public domain image).

Fig. 4: Bastianino (after Titian), Portrait of Alfonso I d'Este with the Order of Saint Michael necklace, Florence, Galleria Palatina at Palazzo Pitti (3D model).

The selection of artworks chosen by Ippolito to be transported to France responds to precise cultural policy choices: Mazzolino's "*vena nordica intemperante [intemperate northern vein]*" (Pattanaro, 2007) would have contributed to making him an appreciated artist at the court of Francis I.

Moreover, confirming his perception as a 'northern' painter are also some erroneous attributions, such as the one that sought to designate the *Massacre of the Innocents* as a painting by Brueghel, formulated at the time of its exhibition in the Tribuna degli Uffizi[4]. As Ippolito returned from France, the two Mazzolino panels found their place in the Roman palace of Monte Giordano, where they appear among the assets in the 1573 inventory, prepared following the cardinal's death[5]. Subsequent documentary evidence allows for the tracing of both paintings to Tivoli, listed in the inventory, drawn up in 1583, of the *guardaroba* of Luigi d'Este, Ippolito's heir[6].

Following Luigi's passing, Roman collectors were immediately ready to attempt to acquire the most valuable pieces of his inheritance: thus, the two works by Mazzolino changed hands, ending up, in 1587, in the collection that Ferdinand I de' Medici was assembling in his villa on the Pincio[7]. Later, in 1607, the *Massacre of the Innocents* left Rome to enter the grand-ducal collections in Florence, where it would be joined by the *Circumcision* only in 1796[8].

Among the paintings that Ippolito brought with him to France, there must also have been one

[4] Palazzo Vecchio 1980, p. 264, entry 492; and see the observations by Longhi [1934] 1956, pp. 69-70.

[5] ASMo, Camera ducale, Amministrazione dei principi, 1349, c. 23r: "*un quadro delli Innocenti con cornice di legno dorate*" and "*un quadro dipintovi la Circoncisione con cornice di noce*"; see Occhipinti 1997, pp. 602-603.

[6] Campori 1870, p. 46: "*un quadro depinto in tavola, dentro l'Innocenti, con cornice dorata con grottesche*" and "*un quadro depinto in tavola della Circoncisione corniciato di noce con una cortina d'ormesino cremisi*".

[7] Archivio di Stato di Firenze [ASF], Guardaroba Medicea, 790, c. 192v, 193: in the "*seconda camera del detto appartamento*" at Villa Medici are the "*quadretto in tavola dell'istoria delli Innocenti con ornamento dorato dipinto a groteschi*" and the "*quadretto in tavola dipinto la Circoncisione di Cristo con ornamento verniciato tocco d'oro*"; see also, ASF, Guardaroba Medicea 79, c. 428s: "*Un quadretto della Circumcisione con adornamento di noce con pero dalli eredi dell'Illustrissimo Cardinale da Este [...]. Un quadretto delli Innocenti chon ornamento di noce coperato chome supra [...]*": Occhipinti 2009a, p. 17, note 95.

[8] For the presence of the paintings in Ferdinand I's collections and their subsequent transfers until their arrival in Florence, see Cecchi 1991, pp. 500-502; Barocchi and Gaeta Bertelà 2002, I, p. 83 and note 280; and A. Cecchi, in Cecchi, Gasparri 2009, n. 88, p. 86 (the *Massacre of the Innocents*, as anonymous Ferrarese) and n. 95, p. 92 (the *Circumcision*, as Mazzolino).

of the then-circulating derivations of Titian's portrait of Alfonso I d'Este, of which two versions existed: the one painted around 1523, mentioned by Vasari together with the portrait of Laura Dianti[9], and the one commissioned by the heir Ercole II, produced between 1534 and 1536. Both originals are lost.

The first portrait is known from a fine seventeenth-century copy now at the Metropolitan Museum of Art (Figure 3), which depicts the duke resting his right hand on the "Giulia," the famous cannon made from fragments of the bronze statue of Julius II cast by Michelangelo between 1507 and 1508 and placed on the façade of San Petronio in Bologna, but destroyed in 1511; the second varies the position of the artillery piece, but especially replaces the jewel hanging from Alfonso's neck with the prestigious collar of the Order of Saint Michael, and is known through a copy now in Palazzo Pitti in Florence (Figure 4)[10].

In any case, evidence that Ippolito already had a version of his father's effigy during his French years comes from a letter from the Este ambassador Giulio Alvarotti to the Duke of Ferrara Ercole II, dated May 17, 1546, which recounts Francis I's visit to the study of Ippolito's residence, the Grand Ferrare, built by the architect Sebastiano Serlio[11]. On an unforgettable spring evening, the sovereign was conducted among the cardinal's collections "*a lume di torze, le quali furno tutte torze bianche [by the light of torches, which were all white torches]*": it was then that the King of France saw the portrait, "*e volse che Sua Signoria reverendissima [scil. Ippolito d'Este] le donasse detto retratto" [and wished that His Most Reverend Lordship [scil. Ippolito d'Este] would give him the said portrait]*," to be displayed in the "*gabioneto*," the cabinet, of the castle[12].

Having returned to Rome without his father's portrait, Ippolito must have managed to acquire a new copy by 1567, when, for a few months, Federico Zuccaro worked in Tivoli and had time to

Fig. 5: Federico Zuccaro, Copy of the portrait of Alfonso I d'Este, Stoccolma, Nationalmuseum (Wikimedia Commons image).

draw the effigy of Alfonso I, evidently having access to a copy of the second version of the portrait made by Titian (Figure 5)[13]. Alfonso's portrait had been destined to adorn the walls of the so-called "Quarto Camerino" together with the *Holy Family with the Lamb* by Raphael (Madrid, Prado Museum), the *Schiava* (Florence, Uffizi Galleries) and the *Bella* (Madrid, Museo Nacional Thyssen-Bornemisza) by Palma il Vecchio, and a portrait of Henry II of France presumably made by an artist from the circle of François Clouet.

This information is derived from the inventory of possessions found at Tivoli in 1572, a crucial source for the history of the Tiburtine collections[14]. With the originals of Alfonso's portraits lost, and the copy owned by Ippolito at

[9] See Vasari 1550-1568, 1966-1987, VI, p. 159. The portrait of Laura, Alfonso's lover, is in Kreuzlingen, Kisters collection.
[10] For a summary on the issue of the portraits of Alfonso I painted by Titian, see Burgess Williams 2012.
[11] For Serlio's work as an architect for Ippolito in France, see Frommel 1998, pp. 219-241.
[12] The quotations come from the cited letter of Giulio Alvarotti, which can be read in Occhipinti 2001, CXCIX, pp. 133-135. From the letter it can also be deduced that Ippolito's gifts to Francis I were two: in addition to the portrait of Alfonso I, after seeing a painting whose "*wooden ornament*" had been made by the late Duke of Ferrara, "*for this reason His Majesty also wanted it as a gift and had it brought to the said cabinet.*"
[13] The drawing is in Stockholm, Nationalmuseum, inv. NMH 496/1863, where there are also graphic copies from the *Schiava* (inv. NMH 487/1863) and the *Bella* (inv. NMH 486/1863) by Palma il Vecchio.
[14] Archivio di Stato di Roma, Notaries of the Tribunal A.C., notary Fausto Pirolo, vol. 6039, cc. 356r-387r. On the paintings of the "*Fourth Camerino*", see Occhipinti 2009b, pp. 293-314.

Tivoli also untraceable, it should be noted that between 1563 and 1565 the Cardinal commissioned at least two other copies of the second portrait executed by Titian, assigning the task to the Ferrarese painter Sebastiano Filippi, known as Bastianino: one of these, painted to be given to Grand Duke Cosimo in 1563, has been recognized precisely in the version now at Palazzo Pitti, which we have therefore used for the digital reconstruction; the other may have been intended to fill the gap in Ippolito's picture gallery, which was left without a portrait of Alfonso after the gift to Francis I[15].

3. *Shape and optical surface reflection model*

In this section is presented how the optic reflections are modelled. Both workflows proceeded through RAW conversion and colour correction phases. The modelling of optical behaviour in painting surfaces addresses phenomena across three distinct scales (Anderson, 2021): the *microscopic* scale influencing surface reflections and perceptual attributes of color, brilliance, and transparency; the *mesoscale* describing surface roughness; and the *macroscopic scale* defining overall object shape.

Solutions were developed for each scale beginning with RAW image conversion and colour correction.

For both mesostructure and macrostructure analysis, custom software based on PS methods was developed to measure surface normals at each point. For microstructure's characteristics, an analytically approximated BRDF from the Cook-Torrance physical model, with values collected

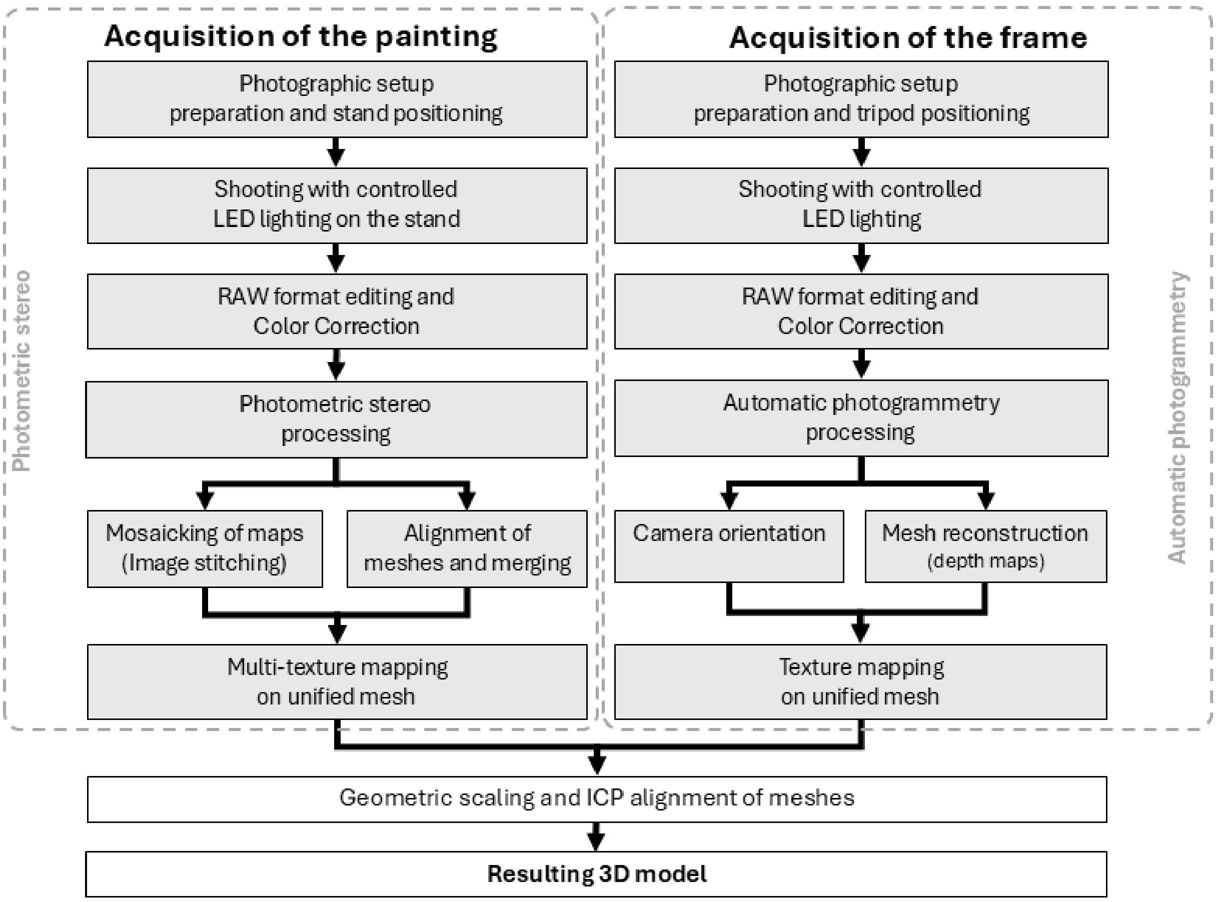

Fig. 6: The digitization workflow.

[15] See the documents published by Venturi 1882, p. 30, notes 2 and 3; Occhipinti 2009b, pp. 307-308, note 53. Recently, the attribution to Bastianino of the painting at Palazzo Pitti has also been accepted by Pattanaro 2021, cat. RA6, p. 246, with bibliography. It is from this version of Alfonso's portrait that Cristofano dell'Altissimo, almost thirty years later, between 1588 and 1592, derived a reduced format copy to be included in the series of illustrious men in the Uffizi Gallery: Barocchi and Gaeta Bertelà 2002, I, pp. 92-93.

Fig. 7: The use of the mobile vertical stand, accommodating the Relio² LED lights and the camera in a unique rigid rig (a) and the horizontal baseline for the frame's photogrammetry (b - Palazzo Pitti in Florence, June 2024)

from the scientific literature, was later implemented (Cook and Torrance, 1982).

The processing approach addresses the reproduction of objects with all their formal properties and optical reflection characteristics of surfaces, to align with what the *Commission Internationale de l'Eclairage* (CIE) defines as "*total appearance*" (CIE). It is essentially a faithful transposition of reflectance properties and microgeometry of artifacts through a process covering three main areas: goniometric validation of surface properties through their BRDF, radiometric accurate simulation of light transport, and perceptual correction producing final images adjusted for human visual perception.

The adopted pipeline combined *photometric stereo* (PS - Woodham, 1980) and digital photogrammetry techniques (Remondino et al., 2011) to create comprehensive 3D models of the *Massacre of the Innocents* and the *Circumcision*, both oil on wood panel, and the *Portrait of Alfonso I d'Este*, oil on canvas.

In detail PS was used to acquire optical reflectance properties of the paintings, while photogrammetry was used to acquire the 3D shape of the paintings' frames.

4. *Techniques and methods for digitization*

The acquisition process was structured as in Figure 6, which outlines two parallel processing streams for paintings and frames that converge in the resulting 3D models production. Two distinct configurations for the equipment were used for PS and photogrammetry.

The workflow for both is detailed as follows.

4.1 Photographic Setup and Preparation

Paintings were digitized at *Le Gallerie degli Uffizi* and *Palazzo Pitti* in Florence, during May and June 2024, with the setup of the photographic stage assembled in place (Figure 7a). For the documentation of paintings' surface, a custom-built, movable, vertical stand was used, which accommodates both LED lighting arrays and the camera (Bacci et al., 2023).

It was designed to allow vertical and horizontal translations, and it ensures the preservation of parallelism between the camera and the painting plane by using two laser distance meters capable of guaranteeing precision of ± 1.5 mm.

For the frames' acquisition, the photographic setup used a conventional tripod system incorporating a lateral sliding baseline mechanism, allowing controlled camera movement to achieve the stereo baseline requirements necessary for photogrammetric reconstruction, while maintaining photographic consistency and image overlapping across the three-dimensional frame elements (Figure 7b).

4.2 LED Lighting and Image Acquisition

The acquisition of the optical reflectance properties of the painting relied on an invariant geometric configuration light-camera exploiting the custom-built stand and the LED arrays.

This lighting system consists of eight directional groups of 4 single LED positioned at

Fig. 8: The custom-built stand as assembled at Palazzo Pitti in Florence (June 2024).

two distinct angles: 45° and 15° relative to the painting's plane (Figure 8).

This approach improves upon the standard procedures for paintings that are typically based on three or four shots (Berns, 2001; Berns et al., 2012) by enabling better measurement of specular reflection and more correct separation between specular and diffuse components, to properly model the albedo. Lights consist of Relio² (Relio², 2025) lamps that provide a spectral power distribution with chromatic reliability at all wavelengths. Their main technical features are in Table 1.

The camera used in the acquisition of the paintings was a Hasselblad H6D-400C equipped with HC Macro 4/120 II lens system (Table 2).

Given that the custom stand covers a capture area of 500 x 375 mm at 11656 x 8742 pixels per frame, a minimum 50% overlap between adjacent images was ensured in the capturing process.

For the acquisition of the frames, a photographic commercial solution with two Godox SL150III LED lamps on stands were used, while the camera was a Hasselblad X2D-100C camera equipped with XCD 2.5/38V lens system (Table 3).

Tab. 1: Light devices used in the acquisitions in Florence.

LED-light illuminators: *high flux LED* Relio²	
Number of LED lamps	32 (8 groups of 4 lamps)
Color Correlated Temperature (CCT)	4,000°K
CRI ratio in output	>95%
Exercise temperature	20° C

Tab. 2: Camera equipment used for paintings' surfaces.

Camera device: Hasselblad H6D-400C	
Sensor type	100MP CMOS
Sensor size	53.4 x 40 mm
Image size	11656 x 8742
Color depth	48 bits
Lens system: Hasselblad HC Macro 4/120 II	
Focal length	120 mm
Max aperture	f/4

Tab. 3: The camera equipment used for digital photogrammetry of frames.

Camera device: Hasselblad X2D-100C	
Sensor type	100MP CMOS
Sensor size	43.8 x 32.9 mm
Image size	11656 x 8742
Color depth	48 bits
Lens system: Hasselblad XCD 2.5/38V	
Focal length	38 mm
Max aperture	f/2.5

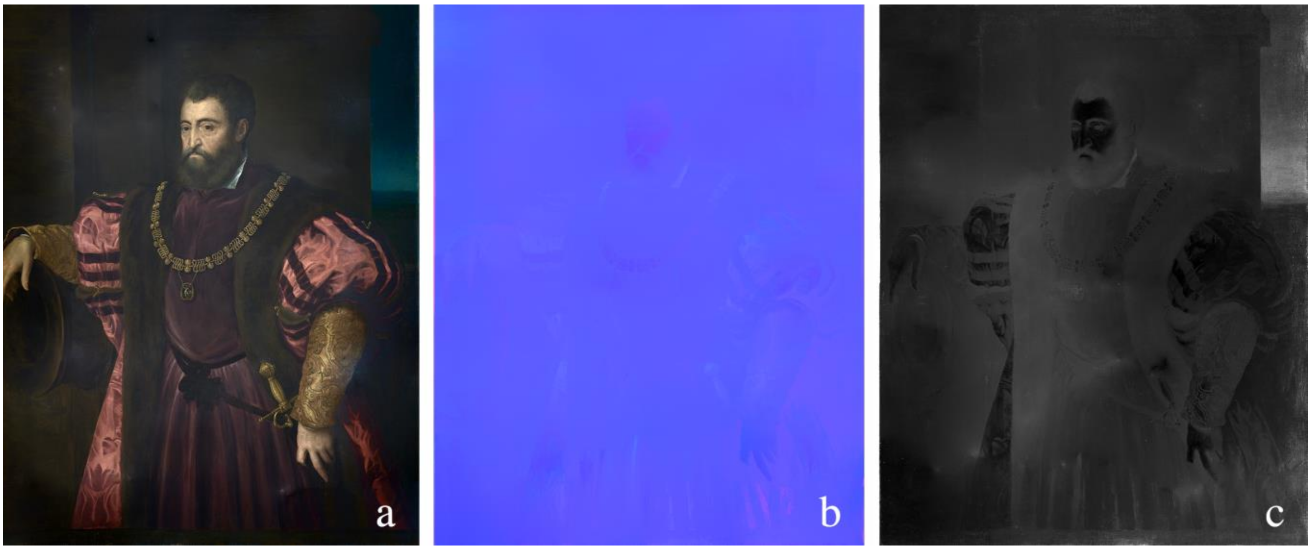

Fig. 9: *Portrait of Alfonso I d'Este:* the albedo map (a), the normal map (b), and the specular map (c).

4.3 RAW conversion and Color Correction

The photographs were captured on both cameras using the .FFF format by Hasselblad, then exported through Hasselblad Phocus software as 8-bit TIFF files with Display P3 color space, while subsequent processing was performed in linear 16-bit, with the processing workflow consisting of *Color Correction* (CC) to achieve the final intended color rendition of the images.

The CC process utilizes an automated target-based solution employing a Calibrite ColorChecker Classic reference chart during image acquisition. Processing is performed using the custom SHAFT - *SAT & HUE Adaptive Fine-Tuning* software (Gaiani & Ballabeni, 2018), which operates through three fundamental processes: RAW image linearization, exposure equalization with white balance adjustment relative to the D4 patch, and a sophisticated three-phase color correction algorithm. The implementation of SHAFT with the digitization equipment achieved a remarkably low CIEDeltaE 2000 color difference (approximately 0.89), indicating optimal color accuracy for the acquired paintings (CIE, 2014).

4.4 Photometric Stereo and automatic photogrammetry processing

The pipeline diverged into specialized processing streams at this stage; this way, it was differentiated as follows.

4.4.1 Surface Reconstruction for painted surfaces

Following the PS processing, the digitization pipelines proceeded through specialized surface reconstruction using a custom software called *nLights*. This piece of software, as happened with SHAFT, was developed and refined over the years by the research group.

nLights is a customization of the *MATLAB PSBox toolbox*[16], designed to be coupled with the custom stand built for the image capture phase. *nLights* produces the following as outcomes (Figure 9):

- An *albedo map*;
- A *normal map*;
- A *depth map*, by integration of estimated normal vector field;
- A *reflection map* generated as the difference in the apparent color with the albedo;
- A *mesh* with a resolution of a vertex for each pixel. The z depth is inferred from the depth map, and a Delaunay triangulation generates the mesh.

The following improvements to *PSBox's* implementation have been introduced with *nLights*:

- a nearby light source model is used, so lamps can be modeled as a distant point light (this is possible when the working distance from an illuminator to an object surface is more than

[16] The MATLAB PSBox toolbox is available for free download at this web URL https://github.com/yxiong/PSBox.

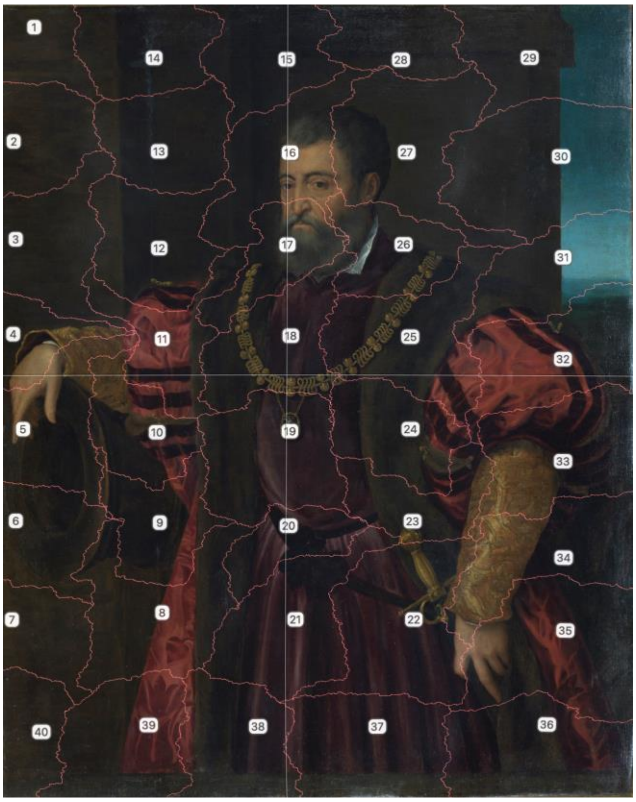

Fig. 10: Seams and camera network for the stitched images of the *Portrait of Alfonso I.*

five times the maximum dimension of the light-emitting area). The position and direction of the light were found through measurement of the mutual position of the camera, lights, and acquisition plane. At the end of the PS process, the maximum errors are no more than 0.1 pixels in the final normal map (maximum angular difference of 0.5° in the evaluation of the direction of the normal) and no more than 1 mm in the mesh;
- the normal integration method was improved exploiting solutions that can run on non-periodic surfaces and manage the mesh's flatness with a different mathematical approach (solving the discrete approximation of the Poisson equation using discrete Fourier transform instead of discretizing it);
- the most common solution to the problem of wrong representation of the surfaces from photometric normals at low frequencies is to replace them with the more accurate ones from a surface measured with a laser scanner, or a probe, or a photogrammetric process. *nLights* uses the distribution of light irradiance sampled from a flat reference surface instead. The non-uniformity of the radiance distribution is compensated using the reference images. In practice, a flat surface that covers the whole light field is measured and the normal field is calculated. Different normal values are qualified as systematic distortions, and their value is subtracted from the normal field of the represented object. With this solution, there is no additional significant time cost required to solve the PS problem, as the procedure remains a linear problem.

4.4.2 Surface Reconstruction in Photogrammetry for frames

The photogrammetric reconstruction process employed a camera network with 25% overlap between orthogonal captures relative to the painting plane, maintaining a *Ground Sample Distance* (GSD) of 0.1 mm. Based on the Shannon-Nyquist theorem, which states that the resolution required for proper sampling must be at least twice the inverse of the finest detail amplitude, sampling was performed at 0.05 mm. (Nyquist, 1928). The camera network was planned before the on-site acquisitions to be sure to cover the entire geometries of frames. The number of shots required for each painting and their respective frames is detailed in Table 4.

Tab. 4: Synoptic table of photographic shots taken.

Massacre of the Innocents (wood panel)	
Acquisition method	Photometric Stereo
Number of images	36
Shooting scheme	2 rows x 2 columns
Massacre of the Innocents (frame)	
Acquisition method	Digital photogrammetry
Number of images	60
Shooting scheme	Lateral shots (50% overlay)
Circumcision (wood panel)	
Acquisition method	Photometric Stereo
Number of images	18
Shooting scheme	2 rows x 1 column
Circumcision (frame)	
Acquisition method	Digital photogrammetry
Number of images	104
Shooting scheme	Lateral shots (50% overlay)
Portrait of Alfonso I (canvas)	
Acquisition method	Photometric Stereo
Number of images	360
Shooting scheme	8 rows x 5 columns
Portrait of Alfonso I (frame)	
Acquisition method	Digital photogrammetry
Number of images	288
Shooting scheme	Lateral shots (50% overlay)

4.5 Mosaicking of images

The workflow proceeded through systematic mosaicking of all the produced maps via image stitching algorithms and mesh alignment operations.

The image stitching pipeline involves feature detection using *Scale-Invariant Feature Transform* (SIFT) to identify keypoints across overlapping images, followed by feature matching and homography estimation through *Random Sample Consensus* (RANSAC – Fischler and Bolles, 1981) to eliminate outliers and establish geometric transformations between image pairs (Szelisky, 2022).

Final blending is reached by Poisson approach, producing seamless complete reconstructions with consistent illumination and minimal visible boundaries (Figure 10). The mosaicked maps for albedo, normals, and specular properties produced high-resolution images subsequently utilized for multi-texture mapping, generating gigapixel maps[17] through the integration of multiple overlapping captures.

4.6 Geometric Scaling and Alignment

This integration phase combined both acquisition streams through geometric scaling, achieved by bringing models to correct dimensions through scaling with references measured directly from the original artworks, and *Iterative Closest Point* (ICP) point-to-plane alignment procedures of meshes (Chen and Medioni, 1992) through the CloudCompare software (2025). The resulting threshold RMS was less than 0.1 mm. The alignment of the images with the 3D mesh, a typical problem of image-to-geometry registration [Pintus et al., 2017] was performed by exploiting registration methods on a statistical basis based on reciprocal 2D/3D information as in *Mutual Information* (Corsini et al., 2009).

Once these activities ended for each painting, the final 3D models were ready for light simulations.

5. Visualization

An interactive *Real-Time Rendering* (RTR) visualization environment was established to display digitized artworks with attention to replicating material features. Unity 3D (2025) was selected as the RTR environment due to its real-time dynamic visualization engine, commonly implemented in high-end graphics applications.

The painting models were prepared with multilayer textures and exported in .FBX interchange format, which handles complex multilayer texture configurations and facilitates importing in the visualization software, to position paintings on the walls of the three-dimensional reconstruction of the *Quarto Camerino* at Tivoli (Figure 11).

Custom shaders were implemented to incorporate not only gigapixel maps but also to consider mip-mapping texture optimization techniques (Williams, 1983) that create multiple versions of the same texture at different resolutions, forming a pyramidal chain.

This approach basically consists of writing a shader using the *High-Level Shading Language* (HLSL) that implements customized versions of the Torrance and Sparrow BRDF model for the two materials:

a. wooden painting frames,
b. wooden or canvas painting surfaces.

Fig. 11: Shaders' structure in the RTR visualization environment that combines multitexture maps (overlaid albedo, normal and specular maps) to simulate light behaviors of paintings.

[17] Gigapixel imaging represents ultra-high-resolution photography techniques that combine numerous pictures to create images containing a huge number of pixels, enabling detailed visualization and zoom capabilities far beyond conventional single-shot photography.

Fig. 12: The RTR visualization of the 3D model of the *Massacre of the Innocents*. The model as lightened by virtual diffuse lights (a) and raked ones (b), highlighting the wooden panel's irregularities.

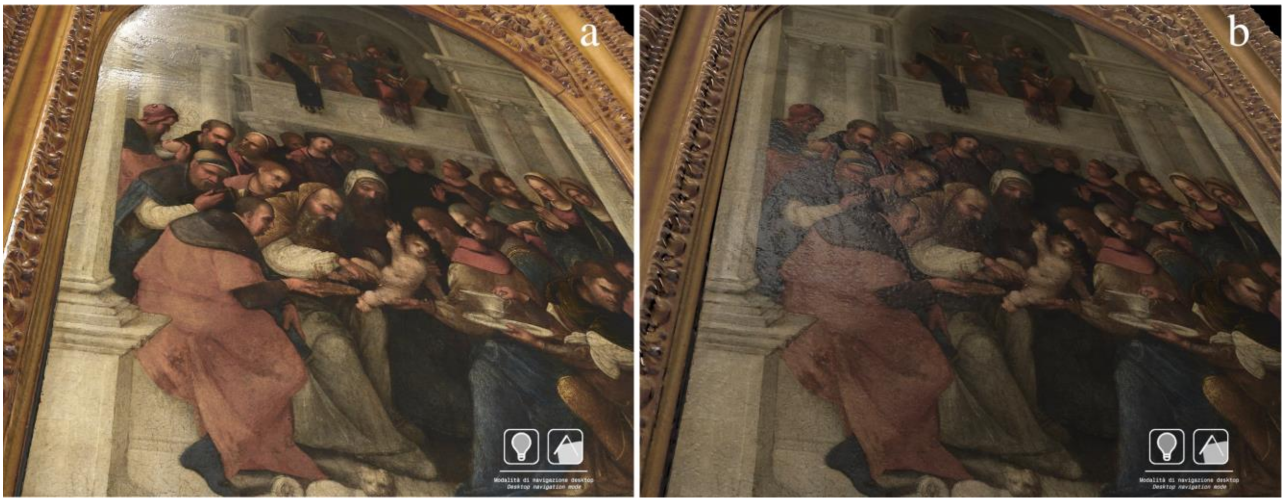

Fig. 13: The RTR visualization of the 3D model of the *Circumcision*. The model as lightened by virtual diffuse lights (a) and raked ones (b), highlighting the wooden panel's irregularities.

The shader architecture incorporates essential material attributes including mip-mapped albedo color mapping, surface specularity parameters, normal mapping, and luminance properties in the form of custom diffusion profiles associated with the materials. The general mathematical formulation for this micro-faceted model for isotropic materials is represented by:

$$f(l,v) = \frac{c_{diff}}{\pi} + \frac{F(l,h)G(l,v,h)D(h)}{4(n\cdot l)(n\cdot v)} \quad (1)$$

where:

- c_{diff} = light portion diffused by the albedo;
- $F(l,h)$= Fresnel reflectance; a term that calculates the fraction of light reflected by an optically flat surface. Its value depends on two factors: the angle between the light vector and the normal surface and the *Refractive Index* of the material (RI). Since the refractive index can vary over the entire visible spectrum, the Fresnel reflectance is a spectral quantity;
- $G(l,v,h)$ = statistical amount of microfacets occluded or shaded by the surface shape when hit by light along the l direction toward the v view vector, considering the h normal for every facet;
- $D(h)$ = normal distribution function for every microfacet; $D(h)$ expresses the number of microfacets with normal equal to h and determines the size, brightness, and shape of the specular illumination;
- $4(n\cdot l)(n\cdot v)$ = correction factor that considers quantities that must be transformed between the local space of the microfacets and the global one for the entire surfaces.

Customization of the formula concerning the surface reflectance for oil painting, which play a

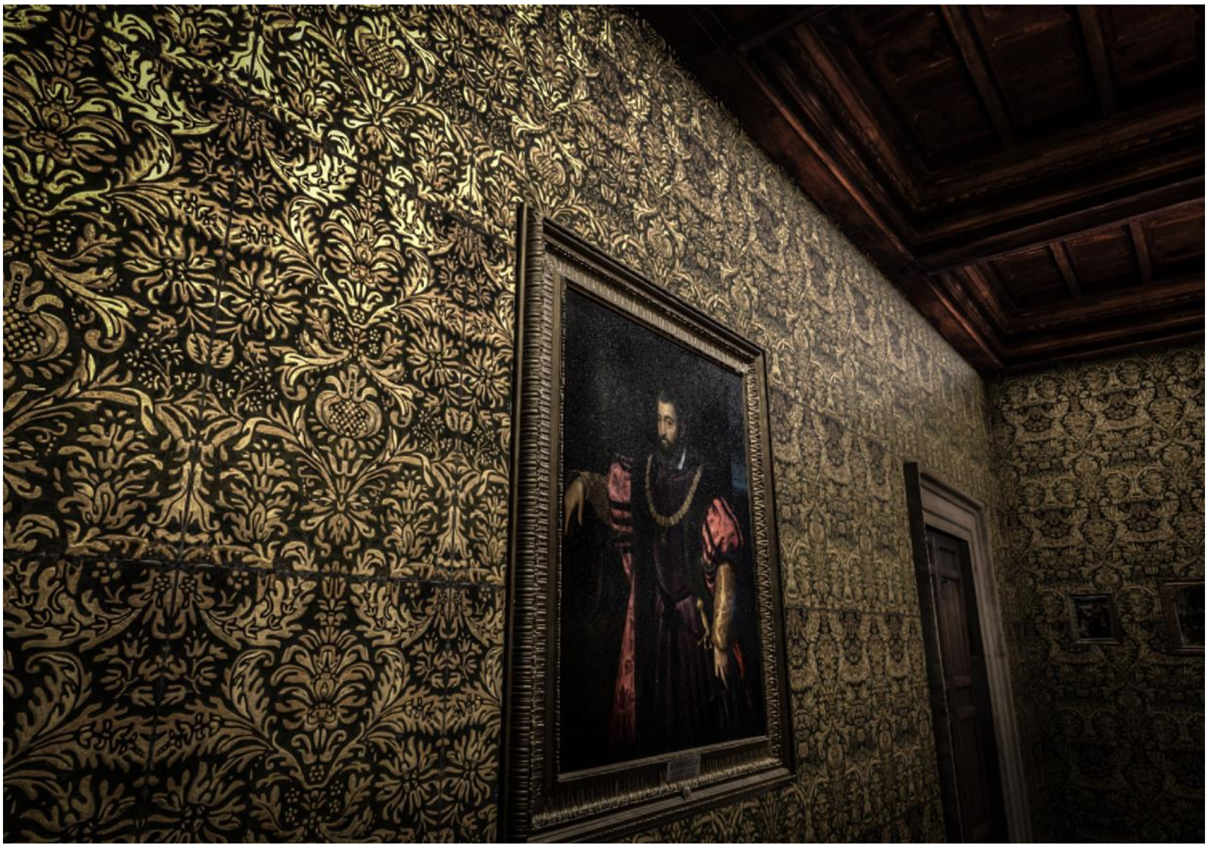

Fig. 14: The interactive RTR model of the reconstructed "*Quarto Camerino*", with the walls covered with leather stripes (*corami*) adorned with gold: the behavior to light of this material was simulated.

key role in the perception of figuration, were modelled following (Stuyck et al., 2017).

Since the digitized paintings consist of oil paint on wooden panels and on canvas, the custom shader was individually modified to replicate the optical behaviors of both conditions. Since their BRDF could not be measured without being in a specialized laboratory, its values for the shaders were inferred by scientific literature and characterized in profiles including the RIs for the Fresnel reflectance component as follows.

5.1 Oil on wood panels and canvases

Oil paint represents a complex viscoelastic medium characterized by colored pigments suspended in oil, whose slow-drying properties enable extended working periods and gradual artistic development. The high pigment concentration imparts non-Newtonian characteristics, including shear-thinning behavior that allows the paint to flow smoothly underbrush application while maintaining structural integrity when shear forces are removed. This unique rheological behavior results in distinctive surface features such as preserved brush textures and paint overhangs that significantly influence the optical properties and visual appearance of the final artwork. A shader system able to reproduce these behaviors was developed to simulate oil paint both on wooden panels and canvases. The Fresnel reflectance component in (1) controls subsurface light scattering through the translucent paint layers, utilizing *Refractive Index* (RI) values that govern how light bends and diffuses through the micro-faceted material in a process of multiple scattering, until absorption or exit occurs (Berns & de la Rie, 2003).

The RI of oil paint, typically around 1.48, varies based on the source plant, environmental conditions, and preparation methods, with values potentially reaching 1.515-1.520 for specialized oils like wood oil, and increases over time due to polymerization of polyunsaturated triglycerides and carbon conjugated bonds, though this enhancement eventually plateaus and may decrease due to deterioration of the cross-linked network structure (Townsend, 1993).

Oil on canvas and oil on wood differ in their support materials, which can influence the final appearance of the painting.

Fig. 15: The interactive RTR model of the reconstructed "*Quarto Camerino*", with the digitized textured paintings hanging from walls, among some other artworks.

Fig. 16: A detail of the decorated walls hosting the digitized painting *Massacre of Innocents*.

RI difference between oil paint on wood versus canvas primarily depends on substrate absorption characteristics and the resulting oil-support interface properties. The varying degrees of oil penetration into different substrate materials may result in heterogeneous optical properties within the paint layer, where areas of higher oil absorption could show slightly different RIs due to changes in the pigment-to-binder ratio (Kouloumpis et al., 2012). Additionally, the chemical composition and surface texture of canvas fibers create distinct interfacial conditions that influence how light interacts with the paint layer, though these effects are likely subtle compared to the more significant optical contributions of pigment type and overall paint film structure (Berns and de la Rie, 2003).

An average value of 1.55 was chosen for oil on wooden panels for the *Circumcision* and the *Massacre of Innocents*, while an average value of 1.45 was chosen for oil on canvas for the *Portrait of Alfonso I*. This is due to the occurrence that wood creates a smooth surface upon which paint is easily applied to and easily removed from until it starts to dry. On canvas this does not work, and the paint layer absorbs into the texture of the canvas, so it is not as reflective. The RI values were determined considering the restoration records and the condition of the paintings.

6. *Results of the process*

Figures 12 and 13 show the results of the whole process, illustrating the multi-textured 3D models. It is possible, since the light is replicated, to virtually lighten them with diffuse and raked lights. Rather than using standardized elements for components that do not exist anymore, sourced materials from similar structures were used for reference to ensure authenticity, creating a set of granular elements with varying reliability levels. The wooden ceiling and terracotta floor were reconstructed from similar elements found elsewhere in Villa d'Este, while window frames, shutters, and doors were modeled based on existing examples still within the building. Material reconstruction was particularly noteworthy, with wall coverings in leather (*corami*) featuring gold patterns. All surface materials were prepared to be visualized with physically based texturing to simulate their optical properties, as well as paintings. Eventually, 3D models of paintings were positioned on walls, to simulate the viewing distance of a visitor when navigating in first person view into the virtual environment. Figures 14, 15 and 16 show the results of this simulation. This final visualization outcome makes it possible to create, for the benefit of scholars and researchers from different fields, a "digital showcase" consisting of individual digitized items that can be analyzed and studied by users in their original environment.

7. *Conclusion*

This paper presented an integrated process for the digitization of historical paintings in view of their re-illumination with different light conditions, developed within the DSE project. The modeling work on Ludovico Mazzolino's paintings from the Uffizi Galleries and Titian's *Portrait of Alfonso I d'Este* from Palazzo Pitti, presented several significant advantages for re-light simulations. The efficiency of execution, achieved through continuous improvements in both software and hardware tools over the years, led to substantial time savings in set-up and photographic acquisition processes. The perceptual accuracy and high spatial resolution in the 3D models of the paintings led to versatile replicas to use in virtual re-lighting scenarios, supporting the fundamental research aim of the DSE project: recreating the original viewing conditions in which these paintings were experienced during the 16th century. In the future, scholars and researchers will likely be able to take advantage of this process to express new hypothesis on artworks and their production. Furthermore, storing the models in a standard format such as .FBX promotes long-term accessibility and sustainability. The contextualized exploration within the RTR viewer offers customizable functionality to meet diverse requirements, enhancing potential reuse in museum or educational contexts (Saccucci & Pelliccio, 2025), so that the project outcomes remain usable and impactful well beyond their research scope.

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