Accurate Visualization and Interaction of 3D Models Belonging to Museums' Collection: From the Acquisition to the Digital Kiosk

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Since 2019 the authors of this article were involved in the digital acquisition and storytelling of artifacts belonging to museum collections. This work showcases on purpose various related case studies to illustrate key issues in the field. They are the *Orcinus Citoniensis* paleontological finding (representative of a complex geometry to be acquired), the *Annunciation* by Beato Angelico (representative of materials with articulate behaviors to light such as the gold foil and tempera), and the Giovanni Battista Amici's *Microscope* (representative of non-cooperative specular materials). Since they refer to such different contests, they are a valid test field to bring into the discussion methods and techniques for:

- the digitization and interactive representation of multicomponent finds;
- a reliable visualization of pictorial works with complex optical behaviors;
- a cost-effective, rapid digitization of extensive collections with non-cooperating materials.

The article outlines a pipeline from accurate digitization to 3D modeling, texturing, and optimization, culminating in the production of interactive experiences. The aim is the introduction of our experience in authoring high-resolution digital surrogates for scholars and museum visitors, to be explored in museums and cultural institutions through conventional devices or digital interactive kiosks. It emphasizes logistical challenges in photogrammetry for acquiring artifacts, including 3D or 2D objects, paleontological finds, and optically non-cooperating items, with a focus on accurate color acquisition and rendering. The developed pipeline enhances the user experience of 3D digital replicas via visualization apps designed for exhibitions and permanent collections.

CCS Concepts: • **Human.centered computing** → **Human computer interaction (HCI)**; • **Computing methodologies** → **Natural language generation**; • **Applied computing** → **Arts and humanities**;

Additional Key Words and Phrases: Museum, exhibition, digitization, 3D modelling, real time rendering, interaction

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1 Introduction

The Department of Architecture at the Alma Mater Studiorum—University of Bologna has been conducting tests since 2019 in three research areas concerning museums, focusing on:

- the production of optimized 3D digital assets of finds and artifacts from various public collections;
- customized shading and interaction of models inside **Real-Time Rendering (RTR)** applications;
- the development of interactive communication artifacts for temporary or permanent exhibitions based on the combination of large-format touchscreens and built-from-scratch kiosks containing them.

These research branches aim at faithfully reproducing the 3D shape and the "total appearance" of a variety of objects and make them available to a wide public through interaction with digital models, while preserving their artistic or scientific value.

The research progressed in two main stages. The first phase focused on exploring affordable digital acquisition methods for diverse artifacts using everyday smartphones, potentially usable by nonspecialists [1, 2]. Building on this foundation, the second phase concentrated on developing advanced, high-resolution digital acquisition techniques. This latter stage involved creating a custom photogrammetric device specifically designed for capturing high-quality digital representations of paintings and other pictorial works [3–5]. This last topic holds particular importance and poses a particular challenge when aiming to accurately record and replicate the optical behavior of materials and pigments included in the painting and its frame: On the one hand, the surfaces are predominantly flat on the other hand, to achieve a virtual perception consistent with the real vision, a highly detailed 3D documentation of smallest relief is mandatory. Nevertheless, making a digital representation of a seemingly simple yet complex shape (if analyzed at a microscopic scale) is not an easy task, especially when the final output must be interactive within a game engine. As a matter of fact, these applications are not designed for scientifically accurate visualization, as they provide solutions that are seemingly pleasing and realistic, but far from correctly reproducing nonstandard optical phenomena. In this sense, the reproduction of the human perception of paintings and frames cannot be solved by applying material presets, or through an empirical editing of color texture from photogrammetric applications. On the contrary, our pipeline is a complex process that "combines" high-resolution acquisitions (up to 25 μm in geometric resolution) into a set of bitmaps capable of modeling complex light behavior effects.

During the Covid-19 pandemic, we encountered another significant challenge: how to balance ultra-high geometric and texture resolutions with smooth 3D visualization across various game engines. To solve the problem a working protocol (mesh processing and parameterization, texture editing) was developed to keep the appearance of asset consistent once exported towards different game development environments. In this sense we focused on Epic Games Unreal Engine and Unity Technologies Unity, widely considered standard development tools.

Both applications currently employ Deferred Rendering techniques, which involve rendering multiple passes of the geometry, such as Depth, Normal, and Color. Shading is then calculated based on these passes, with only the visible fragments being shaded. This is a reason to implement RTR engines to properly visualize artworks from different perspectives, from time to time.

The "combination" of geometric information into special bitmaps has been an established and widespread problem in various applications for decades [6, 7]; more recently however, the pervasiveness of physically based systems in reproducing the appearance of materials through texture sets [8] has made the topic of digital model optimization an increasingly large field of research, with the consequence of extending the number of parameters to be monitored to obtain homogeneous and consistent results [9].

A further topic developed in the research deals with interaction design, in particular, issues concerning different platforms, devices, and target groups to which the application is addressed. The first is a technical problem directly related to the frame rate supplied by the system while interacting with 3D assets: higher the resolution of both, more powerful the system and its graphic card must be. In this sense, we have a very broad horizon of possibilities ranging from the smartphone/tablet to the workstation, with the obvious design differences involved [10]. The second problem relates to the development of a responsive, user-centered interface that can make the game mechanics behind the interaction intuitive, without the need for training and leading to an "instant" gratification to the visitor. The creation of responsive applications, whose interface is both digital and tangible [11, 12], is correlated with the age and cultural/scientific background of the user. In the case of the youngest requires greater interactivity and the attainment of a satisfying result, along the lines of a video-ludic application. In the case of the adult audience, it demands, through interactive exploration, an understanding of the cultural and technical aspects underlying the creation of the work, through perception enhancement of tiny details that are often not visible from afar [13].

In the cases presented, three emblematic examples will be shown, corresponding to a first target group of young visitors (4 to 12 years old), while the second and the third one focus on adults and teenage audience. In all the three cases, the problem of the medium/device used is relevant for several reasons: The first is economic in nature, since the cost of developing an interactive application in the context of a temporary exhibition requires subsequent adaptability to media other than the kiosk to allow for device-independent use (from a touch screen connected to a PC to common tablets). All this entails solving several technical problems related to the different performance of graphic cards, but also interface problems—perceptive ergonomics of interaction on small video formats. In other cases, i.e., when the application and the kiosk housing the screen are developed for the medium to long term (more than a year's time), issues of artifact wear and tear prevail and thus the supply of a hardware maintenance service.

The tests and application case studies shown come from the collections of **Sistema Museale di Ateneo (SMA)** with Palazzo Poggi and the Institute of Physics in Bologna and from the Museum of the Basilica of Santa Maria delle Grazie, in San Giovanni Valdarno (Arezzo), as later detailed in the following paragraphs. Their setup was built upon the research group's previous experiences, in which the informative, pedagogical, and educational values of installations prepared to explore the 3D models were also evaluated where applicable. The varying age groups and cultural backgrounds of visitors were considered following the process outlined in [14].

1.1 Collections at Palazzo Poggi (SMA) in Bologna

The Palazzo Poggi Museum [15] presents various collections ranging from geography and nautical sciences, military architecture, physics, natural history, chemistry, human anatomy, fossils, and dissected animals collected by Ulisse Aldrovandi. The case studies were chosen to encompass a wide range of shapes and optical characteristics for digital acquisition and reproduction. The aim was to provide general operational guidelines regarding requirements, procedures, and working methodologies.

1.1.1 The Giovanni Capellini Collection. The Giovanni Capellini Museum, part of the SMA, is the oldest geo-paleontological museum in Italy [16]. The aim of this case study is twofold: on the one hand to document a paleontological find of great significance, the *Orcinus Citoniensis*, and on the other hand to create a multidevice application mainly focused on children for the exhibition "*Mente et Malleo. Da Ulisse Aldrovandi a Giovanni Capellini: storie dal primo museo geologico*" (15 October 2022–31 August 2023). As a technical objective, this case made it possible to test low-cost protocols developed in previous tests by applying them to an artifact consisting of several disconnected parts and to make a comparison between active and passive sensors [17].

1.2 Collections at the Institute of Physics in Bologna

Case studies from the collection of the Institute of Physics, founded by Augusto Righi [18] include instruments for scientific investigation and experimental physics: mechanics, optics, electromagnetism, thermology, and atomic physics. The optical properties of the materials used in most of the examples in this collection allow for testing photogrammetric techniques using low-cost digital cameras to obtain photorealistic 3D reconstructions with the application of physically based materials.

1.2.1 *The Giovanni Battista Amici's Microscope.*

Compared to a generic microscope, where light from the object passes vertically through the objective lens and then the eyepiece lens for observation, the microscope designed by the Modenese constructor Giovanni Battista Amici operates differently. In Amici's *Microscope*, now at the Institute of Physics, light enters from a side opening, is reflected towards the objective (on the left), and then directed to the eyepiece (on the right) for observation. The sample to be observed is placed on a support, and the light beam is directed onto it by a lens positioned below. Inside the optical tube, a small mirror at a 45° angle redirects the light beam towards the objective. This objective, being an elliptical mirror, not only functions as a lens but also sends the light back to the eyepiece. Introduced in 1812, Amici's instrument is part of several early 19th-century attempts to construct a magnifying device that did not rely solely on lenses, due to the unsatisfactory correction of objective lenses, but instead used a system of lenses and mirrors to improve observation.

1.3 Collections at the Museum of the Basilica of S. Maria delle Grazie in San Giovanni Valdarno

The Museum of the Basilica of S. Maria delle Grazie in San Giovanni Valdarno (Arezzo, Italy) houses a collection of sacred art, primarily featuring paintings from the Florentine Quattrocento, some 17th-century canvases, and sacred furnishings such as silverware and liturgical vestments. Established in 1864, opened to the public in 1990, and newly arranged in 2005, the museum collects artworks ranging from the late 1300s to the mid-1600s, with a primary focus on the Florentine Renaissance. It includes late Gothic works by Mariotto di Nardo and Giovanni Del Biondo, and paintings by artists influenced by Masaccio's modernity, such as Mariotto di Cristofano and Giovanni di ser Giovanni (known as *Lo Scheggia*), Masaccio's younger brother. The collection's masterpiece is the *Annunciation* by Beato Angelico, one of three Annunciations on panel painted by the Dominican friar, alongside those in the Prado Museum in Madrid and the Diocesan Museum in Cortona.

1.3.1 *The Annunciation by Beato Angelico.*

The *Annunciation* by the painter Beato Angelico is a wide tempera painting with some fine gold foil placed on a wooden support hosted at the Museum of the Basilica of Santa Maria delle Grazie and is considered one of the most important works of the Early Renaissance [19]. For the exhibition "*Masaccio e Angelico. Dialogo sulla verità nella pittura*" (17 September 2022–5 February 2023), the Museum needed a digital high-resolution surrogate to facilitate investigations, restoration planning, and to digitally tell the stories behind the artwork. This case was selected to test a pipeline exploiting three different technologies to get the final 3D model: gigapixel imaging [20] to achieve the needed resolution of the images documenting the painted parts, automatic photogrammetry to acquire the shape of the frame and the painted tables, and photometric stereo [21] to reconstruct optical properties of the surface of the painting.

2 From the Acquisition to the Visualization in Museums

Some of the relevant issues faced within museums pertain to the inherent challenge of granting visitors ample accessibility to artwork, without damaging them. Thus, the chance to engage with exhibits' original objects touching them is a rarity, typically reserved for exceptional circumstances. To tackle this issue, some solutions are proposed as they were developed on specific case studies, in which visitors can engage with digital replicas of museum artifacts, almost as if they were touching the real things. To set these solutions, a proper digitization of artworks and their visualization through dedicated systems are necessary, as we will show in this section.

In the collections of Palazzo Poggi (paleontological finds, sandstone, and marble statues) and Giovanni Capellini museums (fossils), most of the acquired surfaces can be approximated to a Lambertian optical behavior. Our tests led to a workflow based on two acquisition technologies and divided into two different approaches. On the one hand, laser scanning—phase shift and multiple laser stripe technology—for larger fragments and on the other hand, photogrammetric acquisition with both smartphone and single lens reflex cameras. The latter is divided into

Fig. 1. Two different maps (normals and bump) were used to restore the detail at different scale (image by F. Fantini).

two distinct approaches: For the larger pieces (heavy and difficult to move), a network formed by free grips around the object was opted for (average bounding box edge from 300 cm to 100 cm); for the smaller fragments (average bounding box edge from 50 to 7 cm), a rotating table was employed to facilitate and homogenize the sampling of objects [1]. The models resulting from these tests were appropriately filtered to make them lightweight and thus compatible with the most common game engines (Figures 1 and 2) [22].

It is worth emphasizing that the desired type of output presents a strong compression, thanks to the lowering of the number of polygons, and a series of maps with the task of restoring both the apparent color and the high detail typical of acquisitions with active and passive sensors. The technique developed involved the reintroduction of detail at two perceptually different scales: an intermediate one reintroduced using normal maps and a microscopic one obtained thanks to bump maps.

2.1 The 3D Model of the *Orcinus Citoniensis*

For this paleontological find, characterized by a co-operating optical behavior (Lambertian) when digitally acquired with both active and passive sensors, the aim was to achieve a complete documentation with a resolution of 0.2 mm.

As with many similar cases, the main problem to be solved is that of occlusion to light beams or laser signal due to the geometric nature of the shapes to be documented. While the 25 vertebrae are simple solids topologically homeomorphic to a sphere and therefore easily positioned on a rotary table, the skull is more complex because it is characterized by through holes: It is a pluri-connected geometric shape [23]. The areas in the vicinity of the ocular cavities and chest cannot be properly illuminated from the outside and access to these inner areas is even difficult for small photographic devices such as smartphones. To solve this problem, a double survey campaign was therefore carried out, but only for the most complex parts, integrating photogrammetry with multiple fringe projection laser scanners (Figure 3).

The final project envisaged the use of the digital model within an engine for interactive visualization and a game mechanic that did not allow a close view to the individual pieces. High-resolution meshes from our integrated procedure were considered in line with the research purposes in the paleontological field without the need of resorting to high-resolution scanners [24] or X-ray CT scan [25].

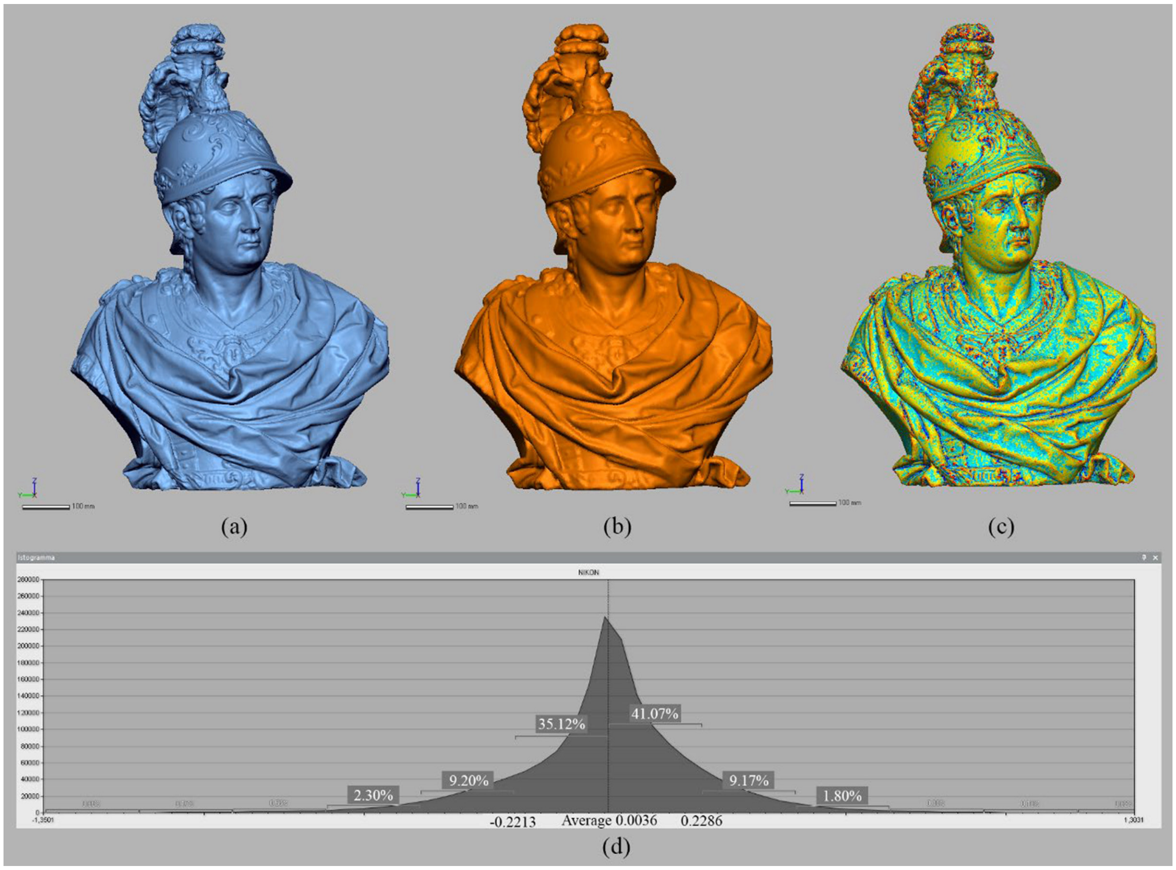


Fig. 2. 3D asset for interactive visualization, reliability check: (a) High-poly (3.453.105 triangles); (b) low-poly (103.014 “quads”); (c) deviation check; and (d) histogram (image by F. Fantini).

2.1.1 Survey Campaign. For the digitization of the *Orcinus Citoniensis* the following equipment was adopted:

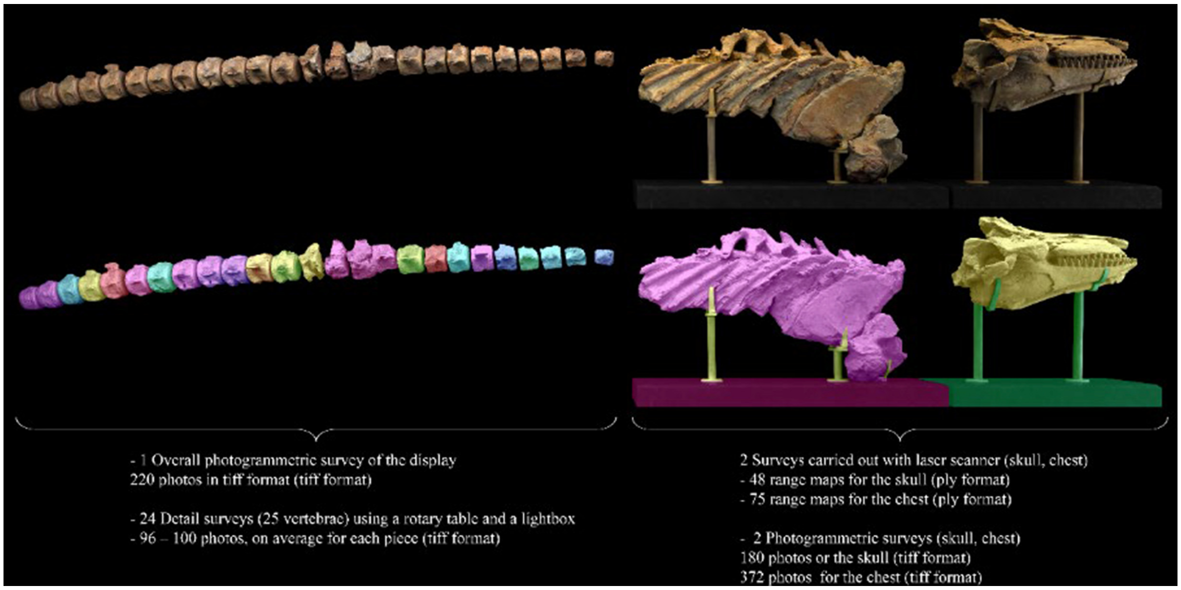
- Nikon D5200 SLR camera featuring 16.2 million effective pixels equipped with an f = 18 mm focal length lens during the acquisition.
- NextEngine 2020i (NextEngine Inc., Santa Monica, California, USA) with operational field of 342.9 × 256.54 mm (wide lens), measurement speed of 50,000 points/s, 0.149 mm resolution, 3D point accuracy of ±0.3 mm.

For the control of the radiometric aspects of the photogrammetric survey, a chromatic target was used for the elimination of the chromatic dominants [2].

For the 25 vertebrae, the following were used (Figure 4(a)):

- a graduated rotating table with Agisoft Metashape RAD coded targets with known spatial coordinates;
- a lightbox photo studio (63.5 × 76.2 × 63.5 cm) equipped with 5,600K LED lighting system.

A “double shell” technique was used to align the photos of the top and bottom of each vertebra. It consists in the creation of two incomplete models: one for the top and the other for the bottom of the vertebra. At this stage, the polygons coarsely representing both the background and the support are eliminated from the polygonal model. For each model the masks are automatically calculated so that the final and comprehensive



- 1 Overall photogrammetric survey of the display
220 photos in tiff format (tiff format)

- 24 Detail surveys (25 vertebrae) using a rotary table and a lightbox
- 96 – 100 photos, on average for each piece (tiff format)

2 Surveys carried out with laser scanner (skull, chest)
- 48 range maps for the skull (ply format)
- 75 range maps for the chest (ply format)

- 2 Photogrammetric surveys (skull, chest)
180 photos or the skull (tiff format)
372 photos for the chest (tiff format)

Fig. 3. Final optimized model and semantics of the *Orcinus Citoniensis* with surveying procedures and corresponding data (image by G. Lecci).

alignment does not consider the noncoherent areas. The technique works if a sufficient area of overlap between the models is photographically documented. For the skull and chest, which are difficult to move and fragile, the same methodology was adopted to carry out the digitization. It consists in the creation of a network centered on one, and then on the other half, of the object with respect to its longitudinal symmetry plane. Each "shell" was acquired using these tools (Figure 4(b)):

- Three RAD coded targets, positioned at known distances, were applied on the respective pedestals of the main anatomical parts of the orca in order to form a 90° angle for the correct verticalization of the models and to scale them.
- Two USB LED Lights on telescopic tripods with stable color temperature of 5,600K; the rotatable mounting head allowed 45° convergent orientation of the lights towards the geometric center of the object.

The technique permits to perform two independent alignments of the respective sets of photos (right side and left side) which lead to obtaining two incomplete mesh models (Figure 5).

The operation that allows the integration of both networks consists in the automatic masking of the subject photos (orca and support) to eliminate inconsistent backgrounds affecting the alignment procedure.

A further survey was also carried out for the vertebrae positioned on the appropriate support which reproduces the shape of the orca's caudal fin. The objective of this survey—intrinsically incomplete due to the occlusions by the metal support rails—was to allow the individual vertebrae to be reassembled in a system consistent with the curvature of this anatomical part without having to carry out manual repositioning operations (Figure 6). The operation consists in the semi-automatic alignment of the high-detail models equipped with apparent color textures on the general model using a reverse modeling application.

2.1.2 Optimization of 3D Assets. In the case of the paleontological find we opted for an automatic technique of lowering their resolution. The individual low-detail pieces were subsequently subjected to parameterization and texturing with the aim of maintaining the acquired detail [9] and even adding further tiny bumps with a filtering


(a) (b)

Fig. 4. (a) Vertebrae acquisition rotary table and lightbox. (b) Skull and chest acquisition setup (image by G. Lecci).

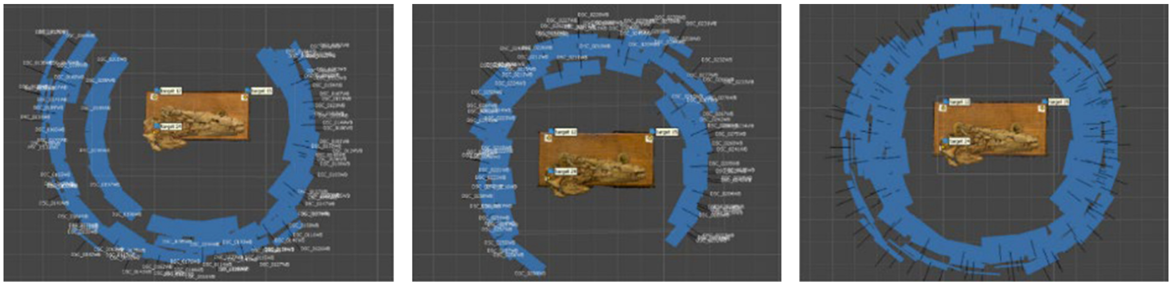

(a) (b) (c)

Fig. 5. (a) and (b) Skull right and left side. (c) Complete skull model after automatic masking and new alignment (image by G. Lecci).

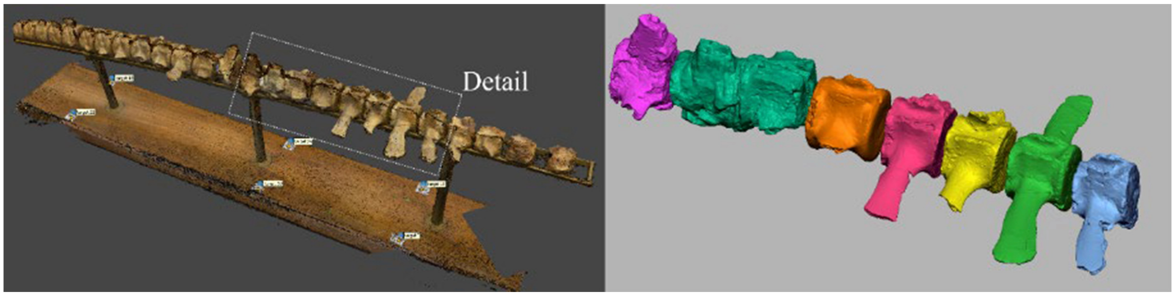


Fig. 6. Photogrammetric survey of the vertebrae and their support and a selection of eight high-resolution vertebrae consistently aligned to the general template model (image by F. Fantini).

and double baking technique. Decimation and improved portability of 3D digital models without resorting to time-consuming direct modeling solutions can be summarized as follows:

- Smart decimation of high-resolution meshes, namely a simplification aiming at improving the asset quality, in terms of vertex sampling, regularity, and density of triangles on the base of local curvature [26].

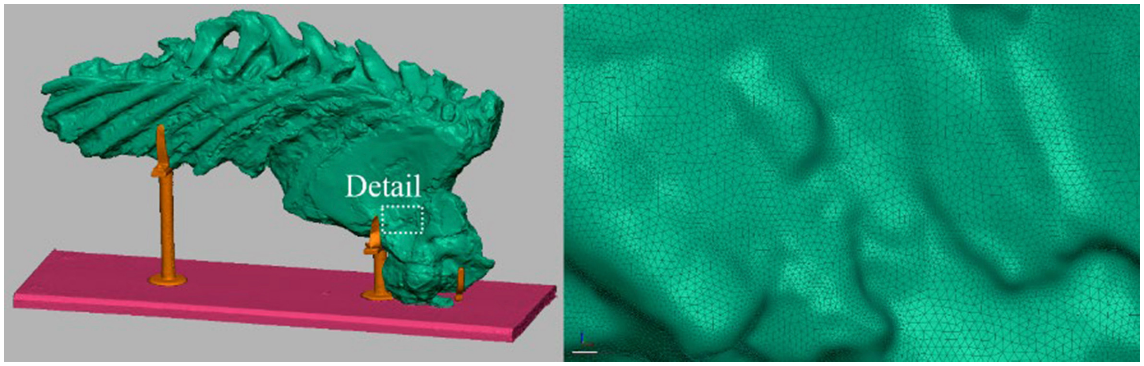
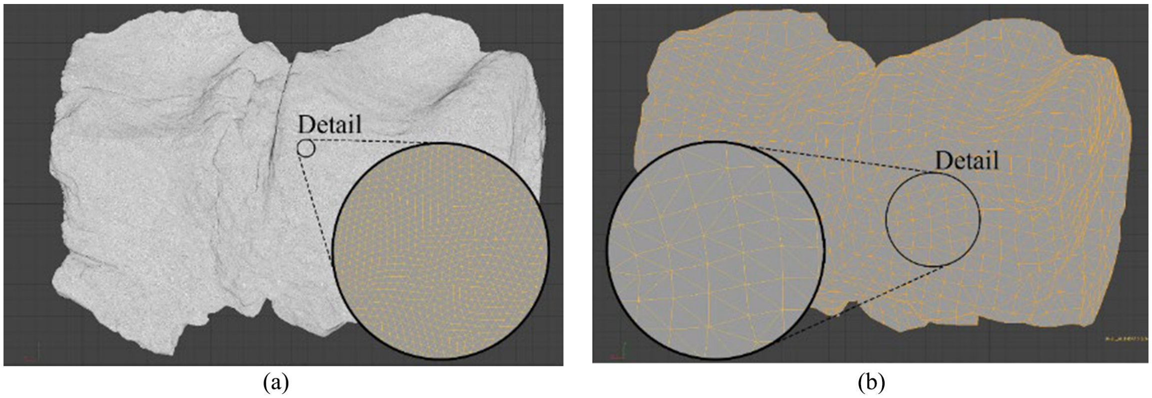


Fig. 7. Chest semantic split and adaptive remeshing (image by F. Fantini).



(a)

(b)

Fig. 8. (a) High-poly from photogrammetry after remeshing. (b) Low-poly quad mesh (converted into triangles) (image by G. Lecci and F. Fantini).

- Progressive meshes, an efficient, lossless, continuous-resolution representation widely spread online [27, 28]. It works by applying a set of three mesh transformations: edge collapse, edge split, and edge swap.
- Retopology [29], widespread in the computer graphics sector and based on manual operations [9].
- Quad-dominant remeshing [30].

The last two solutions are particularly suited to the visualization of 3D models in the context of gaming applications since they produce bands of quadrilateral polygons aligned to the main geometric features of an object while guaranteeing their consistency with local orientation, since they are associated with principal curvature directions.

In both cases the aim is to create a lower resolution version of the starting models which must be previously analyzed and semantically "split" into parts. These parts should present adaptive resolution and absence of topological defects (Figure 7).

The models of each individual find were resampled according to an algorithm which allows for the obtainment of an isotropic pattern of quadrangles with an edge average length of 4 mm and a SD high-poly/low-poly model of 0.6 mm (Figure 8).

The next steps for the preparation of the optimized model are its parameterization in (u, v) space and the definition of hard edges along the boundaries of the islands in parameter space [9]. The low resolution and regularity of the square meshes, consistent with the object's curvature flow, facilitate this operation. The standard workflow would involve converting nonplanar quadrangular polygons into triangles (Figure 8(b)) and then baking them from high to low-detail models to encode the normals in an RGB map applied to the low-resolution mesh [6]. In the case of the *Orcinus Citoniensis*, a capability of the baking process was applied: It allows to merge inside one normal map the contribution from geometric normals as well as micro-cavities and wrinkles from a greyscale bump map (obtained by filtering color texture). The output is an apparent, and additional detail, below 0.1 mm—then not measured—but very useful inside the game engine, to provide final users with a more perceptual representation of the real surface. The technique consists in converting the color map (which is very close to albedo due to the artificial lighting provided) into a bump map using a color-to-grey filter to be applied to the high-detail model from photogrammetry.

The filtering system used, which is very practical in photogrammetry, is the Wallis [31], a variance-based technique with the addition of two parameters (variance gain factor A, mean proportionality factor B) that adaptively adjusts the luminance values of pixels in local areas. Unlike a global contrast filter, Wallis does not apply the same contrast value over the entire image [32].

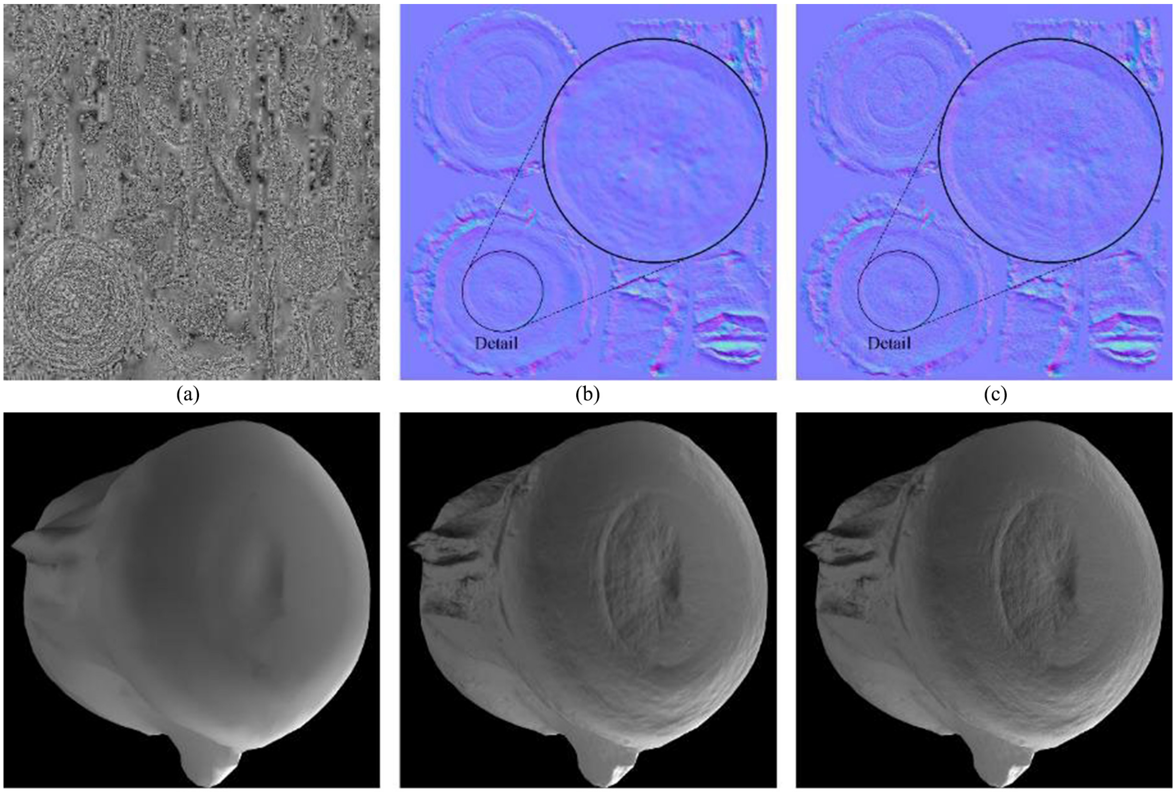
Figure 9 shows the steps in the process starting with obtaining the greyscale image to be applied to the high-poly model (Figure 9(a)). The process of baking the normals that typically involve a high-poly model and a low-poly model (result in Figure 8(b)), in this customization of the standard pipeline, involves the encoding of the apparent normals that overlay the contribution of the high-detail geometry and the bump map (Figure 9(c)). The result is an obvious recovery of microscopic details that are not surveyed but are useful in giving the model a superficial appearance more consistent to the real object (Figure 9(f)).

2.1.3 The Application. The application developed in Epic Games Unreal 4.27 is the result of collaboration with developers, curators, and experts of 3D organic modeling in the field of paleontological reconstructions. The game mechanics are designed for a child audience with an instantaneous learning time and a maximum game duration of a few minutes, based on the puzzle type. Entering the game mode presents a selection of artifact elements (skull, thorax, right fin, and groups of vertebrae) that can be selected and placed on the touchscreen inside a kiosk. A transparent shader has been applied to the skeleton, highlighting the outline to compare the boundary of the model with that of the selected anatomical part. The simulation of the underwater environment is obtained through fast computation solutions: a background gradient, a particle emitter with a long lifetime, and a procedural noise texture on the emittance of light in scenes to simulate the caustic phenomenon (Figure 10).

2.2 The 3D Model of the *Annunciation*

Housed within the *Museo della Basilica di Santa Maria delle Grazie,* the *Annunciation* is a remarkable creation by Giovanni da Fiesole, renowned as Beato Angelico. This inspiring artwork, whose dimensions are 238 × 234 cm including the *predella*, was crafted between 1430 and 1432 in tempera technique, enriched with delicate gold foil accents, all set upon a wooden base. Set within a frame reminiscent of classical architecture, Angelico's masterpiece is adorned with numerous symbolisms referring to the visitation of Archangel Gabriel to the Virgin Mary; the complexity of these details often eludes viewers, whether in standard photographs or even during in-person observation. This difficulty stems from two main factors: the painting's wide dimensions and the necessary distance between the artwork and museum visitors for conservation purposes.

The 3D model of the *Annunciation* was authored combining photometric stereo for the painting panel and automatic photogrammetric techniques for its wooden frame, to ensure the essential "total appearance" [33] and employ a simpler and less invasive digitization process compared to other methods such as laser scanning, while still yielding accurate outcomes and following already tested workflows as detailed in [9]. The choice to digitize through exclusively photographic systems arises from the desire to be as minimally invasive as possible towards the artwork. Moreover, by adopting tools that are easy to use, even by nonspecialized personnel, it becomes possible to expand the potential use of the proposed acquisition method. More broadly, this aspect evidently enables a wider range of museum operators to update or independently supplement the digital documentation of



(a) (b) (c)

(d) (e) (f)

Fig. 9. (a) Wallis' filter applied to the color map of the high-poly model. (b) Standard baking from high-poly to low-poly perfectly working at meso-scale but less efficient at micro-scale. (c) The normal map baked with our technique. (d) Rendering of the low-poly model. (e) The same model with a conventional normal map applied. (f) The final result: bump and geometric normal encoded in a single RGB map (image by F. Fantini).

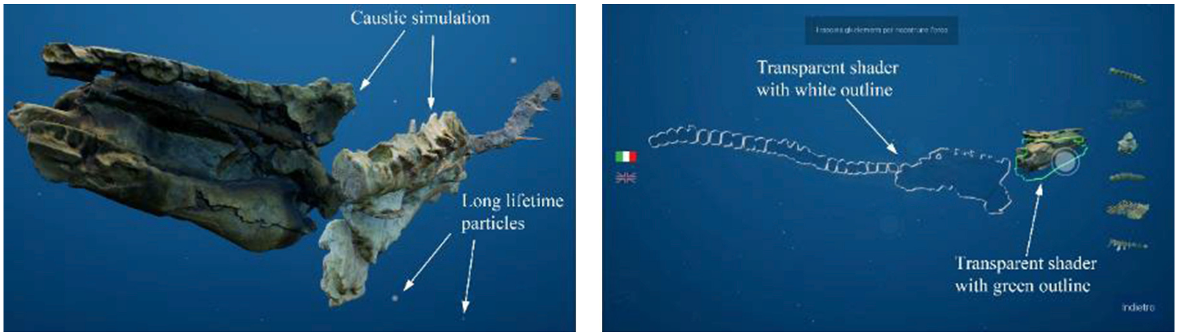


Fig. 10. Interactive application of the *Orcinus Citoniensis*. Environment and lighting, game mechanics (image by F. Fantini).

their collections. The use of multispectral methods, while allowing analyses capable of providing a wealth of information, can also be potentially hazardous for the preservation of paintings as well as prolonged illumination to document them, as reported in some works in scientific literature [34, 35]. Therefore, based on the results

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	11,600 × 8,700 px	5760 × 3840 px
Pixel size	4.6 µm	6.25 µm
Focal length	120 mm	100 mm

obtained in previous research experiences, the *Annunciation* was digitized using entirely passive acquisition processes and photographic-based tools.

2.2.1 The Acquisition. The process of turning paintings, and more in general museum artworks, into their digital replicas using photography often requires different tools, mainly digital cameras, along with their additional equipment. Usually, the most precise results require expensive specialized equipment, which are not common in the museums' set of tools, and which need also skilled operators. For the *Annunciation*, the acquisition was performed with custom-made tools backed by high-end camera devices. In Table 1 the cameras used for the digitization of the painting are reported, while in Figure 11 the custom stand hosting the camera and selected LED lights set is represented.

This setup was fundamental to create a controlled environment, in which angles and distances were checked and maintained through the whole acquisition.

The acquisition network to cover the full painting for the photometric stereo was planned with a minimum 25% overlap between adjacent pictures so that, by image stitching techniques, they can be later joined to compose a higher resolution image. The pixel density was evaluated using the equation:

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

where PD = Pixel density (in ppi)
S_r = Sensor width resolution (in pixel): 23,200
F_L = Focal length of the lens system (in mm): 120
U_f = Unit conversion factor: 25.4 for PD in inch (ppi)
D = Camera distance to the painting (mm): 1,120
S_w = Camera sensor width (mm): 53.4

Beginning from a reference resolution of 25 mm corresponding to 1,016 dpi, it was planned a camera-to-surface of 1,120 mm allowing a nominal resolution of 1,182 ppi. The area covered for each picture is then 500 × 375 mm. The photogrammetry for the wooden case was planned considering a **Ground Sampling Distance (GSD)** from the equation:

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

where S_w = Camera sensor width (mm): 36
D = Camera distance to the canvas (mm) to be evaluated
imW = Image width (pixels): 5,760
F_r = Focal length of the lens system (mm): 160

Fig. 11. The operations during the acquisition: A custom stand was developed to host cameras and lights perpendicular to the painting's plane, with eight different lights directions and a movable structure to capture the artwork's details at the desired resolution (image by G. Bacci).

To reach the goal of a minimal 50 mm/pixel resolution, the camera distance to the canvas was evaluated in 700 mm, allowing a GSD of 28 mm/pixel.

The maps produced with photometric stereo and the 3D shapes from digital photogrammetry were combined to get a complete digital model of the artwork, as detailed in [3]. The huge amount of data collected, both in terms of dimensions (composed maps are gigapixel images) and mesh resolution, needed to be properly visualized in a museum context to be a valid dissemination tool. The frame and the painting underwent different lightening processing with the aim of preserving the work's qualities (Figure 12). Segmentation was therefore carried out to reduce manual processing time through a semi-automatic approach consisting of:

- Overall quad-dominant remeshing for high frequency details;
- Manual retopology of the regular architectural elements of the frame which can be obtained through simple mesh modeling operations;
- Adaptive remeshing for the painting and the predella.

To achieve the goal of a comprehensive reproduction of the painting, the acquisition of color has also played a significant role in the process. The scientific literature dedicated to technical photography for documenting paintings and their execution techniques is extensive [36, 37]. However, the challenges arising from the need for faithful color representation are manifold. In the acquisition of the *Annunciation*, the research group relied on a proven working solution that was refined over the years, as summarized in [38]. Once the 3D asset and its textures were defined, the goal of leaving visitors free to explore the artifact was possible through the RTR approach [39, 40].

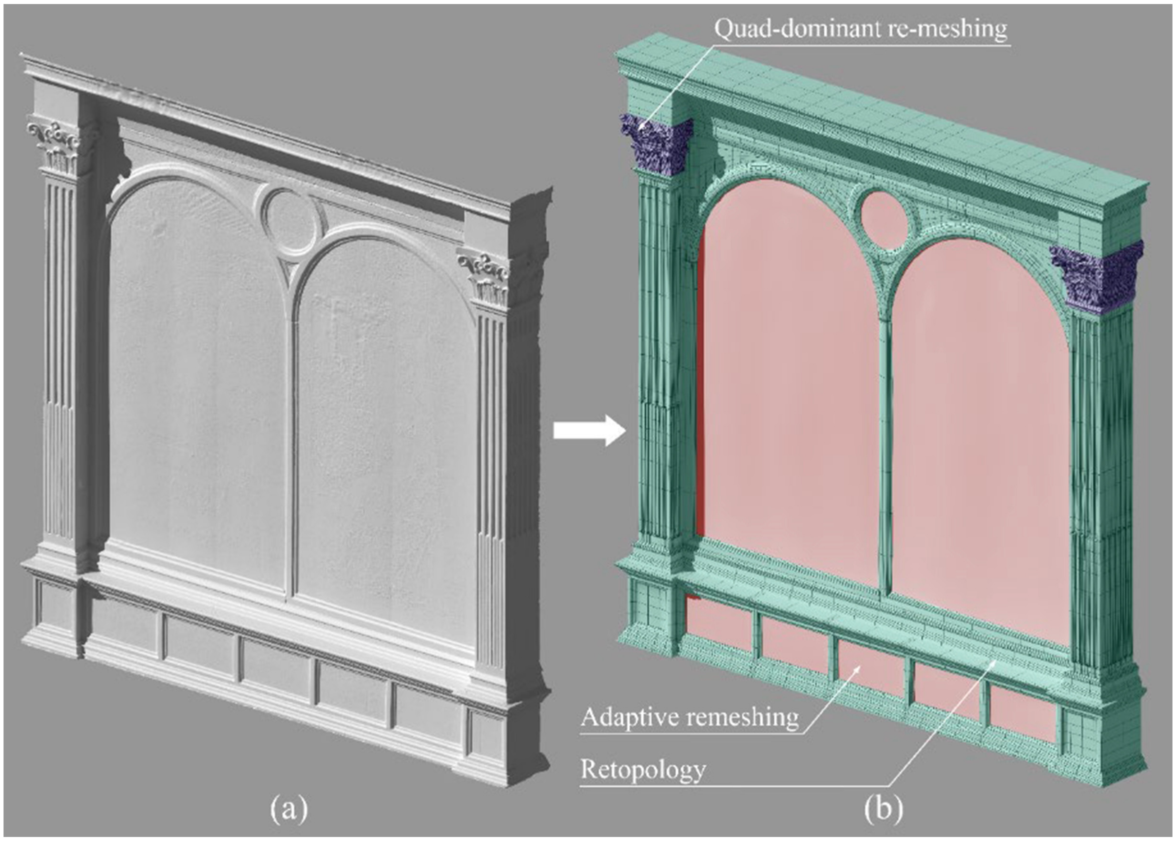


Fig. 12. (a) High-poly models from different acquisition techniques. (b) Optimized model using different methodologies (image by F. Fantini).

2.2.2 The Real-Time Visualization. Paintings are works of art way more complex than a 2D graphic: They include the thickness of their strokes (often useful to better understand painters' techniques), the minute shapes of their supports, the *craquelures* (useful in the preservation state definition), the behaviors to light for the painting materials, and so forth. It is difficult indeed to replicate all these features with simple photographic documentation. RTR offers an entirely different perspective [9], as it allows the free exploration of an artwork, zooming in on details at will, changing the viewing angle to appreciate how surfaces behave when hit by light, or manipulating the artifact in real-time in ways that would not be possible with the original paintings.

To let visitor in the museum explore with the highest detail the digital replica of the *Annunciation*, in fact, a custom interactive application, called *AnnunciatiOn App*, was created within the Unity graphics engine, who proved its adaptability in the management of the complex 3D model shapes integrated by high-resolution texture maps. Unity includes a GUI and a sophisticated *High Definition Rendering Pipeline* [41], which was further developed through custom scripts and shaders to replicate all the materials' behaviors in terms of reflectance, albedo, and roughness, starting from literature [42–45]. Although these were the main reasons for the RTR development engine choice, Unity was preferred to Unreal Engine due to its better adaptability to the C# programming language; apart from a wider community of users who tirelessly publish a huge quantity of online tutorials and resources, Unity proved to be easier to manage also from unskilled IT operators, such as museum curators. They, for example, could follow the application development and check the extended textual contents linked to the 3D models, as

Table 2. Captioned Sections in Which Views Are Organized in the Interactive Interface

Section ID	Section Name	Contents
Section A	The *Annunciation*	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 *predella*	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 *hortus Conclusus*—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

they were guided by Unity's templates specifically prepared. Unreal Engine relies on C++ instead (while including the Blueprint visual tool), and it is more oriented to specialized users [46]. The application was designed to run on kiosks but also on personal computers, so the Unity's feature to quickly compile code targeting different operative systems was considered paramount, since hardware may be extremely variable during the lifecycle of a museum. Also due to this reason, and to optimize performances, Unity was preferred to Unreal Engine since, in this context, the latter is more resource demanding, as detailed in [47]. The resulting runtime application for the *Annunciation* was designed to run in a vertical 9:16 virtual space, in which the 3D model can be explored in a dedicated kiosk in museums, offering the choice between a guided tour that focuses on specific **Points of Interest (POIs)** or a free exploration. Specifically tailored for a 55-inch touchscreen with a supported maximum resolution of 3,840 × 2,160 pixels (4K), the visualization runtime features a couple of on-screen GUI buttons, shaped like arrows within a semi-transparent circle, and designed to be easily tapped with a finger. They allow users to navigate the 3D model, moving forwards and backwards to examine all the fine details of the painting. Explanatory commentary is grouped into distinct sections of interest, as indicated in Table 2. By lightly tapping two additional buttons, users can also activate an automated guided tour. During this tour, the most significant details are sequentially displayed, or users can choose to start over. In Figure 13, the 3D model is represented as displayed by the runtime application and the GUI buttons to explore the captioned sections of the guided tour are visible.

The reliability of the touch interaction system is ensured through custom scripts designed to prevent the selection of multiple buttons simultaneously and to prompt the application to restart if no activity is detected within a set time frame. However, the application's adaptability extends beyond museum visitors, also targeting scholars. For instance, running the application on a personal computer, by pressing the space bar on a connected keyboard, the interface transitions out of kiosk mode allowing users to explore the painting using a regular mouse pointing device. The video resolution, which is typically set to 4K for exhibitions, is automatically adjusted to the highest possible values supported by the connected display, if available. This ensures that the application can accommodate diverse hardware specifications in various utilization settings.

The contrast between the real *Annunciation* and its replica is particularly impactful. Visitors can establish a personal connection with the masterpiece by "touching" its virtual copy, fostering a more intimate engagement with the artifact. To enhance this experience, a dedicated kiosk was devised, taking the form of a wooden case reminiscent of the frame around the original painting. Positioned within the same room near the authentic

Fig. 13. The custom runtime developed to be explored through an interactive kiosk: The 3D model (left) can be zoomed with traditional touch gestures to showcase all the materials' properties such as gold foil under different lights (center), while the guided tour highlights the most remarkable POIs in the painting (right) (screenshots from the kiosk application by S. Garagnani).

Fig. 14. Some artifacts from the "Augusto Righi" physics collection: Melloni's Optical Bench, Sine and Tangent Compass, and Helmoltz Resonators. Most of the objects consist of a limited number of regular geometric shapes such as parallelepipeds, cones, cylinders, and spheres (image by G. Fracascia).

artwork, this kiosk stands as a vertical frame housing the touch screen and containing all the necessary hardware: This includes a workstation concealed behind a removable panel to facilitate maintenance tasks. Its dimensions of 1,100 × 2,200 × 490 mm were chosen with ergonomic considerations in mind. A physical keyboard situated beneath the vertical screen, whose specifications will be later introduced, grants users convenient and direct access to each of the five sections of the guided tour.

2.3 Giovanni Battista Amici's *Microscope*

Non-cooperative specular materials have always been a particularly difficult challenge for both photogrammetry and active sensors. Their optical response is comparable to that provided by matte black, reflective black, and transparent objects [48]: Uncertain results and a considerable amount of post-production work on the 3D models are needed to obtain results visually suitable for interactive representations. Most of the tools belonging to Bologna's Institute of Physics collection, although heavily penalized due to the presence of conductive materials, are made up of combinations of solid primitive shapes that easily fit into a hard-box modeling process (Figure 14).

The suboptimal working condition involves the use of traditional measurement techniques alongside photogrammetric ones to integrate the morphologically inconsistent areas. Taking into consideration the didactic

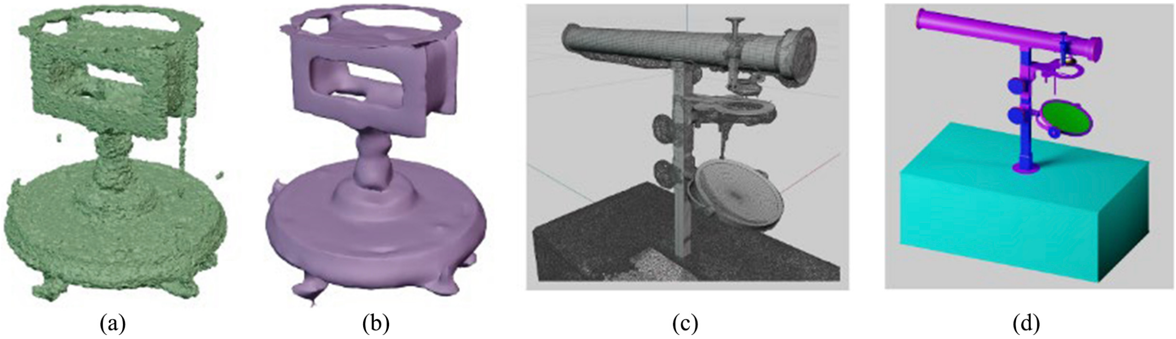


Fig. 15. (a) The resulting mesh of the galvanometer from photogrammetric application; (b) mesh after filtering process; (c) Amici's *Microscope* single unstructured high-poly mesh used as template; and (d) final low-poly structured mesh after fitting quad-primitives (image by G. Fracascia).

and illustrative purposes through RTR, this hybrid approach to modeling did not compromise the final result which however required prolonged manual processing times for both modeling and texturing performed starting from photographic materials edited within specific authoring programs aimed at physically based solutions.

2.3.1 Acquisition and Modeling. Surveying activity, in this case, was carried out using nonprofessional photographic equipment (compact cameras), and additional low-budget tools aiming at containing acquisition issues outlined above (mainly to filter and diffuse natural light). Gold surfaces exhibit the classic anisotropic reflections—typical of metalworking through lathe—but also small the signs of time that mitigate unwanted optical phenomena. To enhance the mesh quality from photogrammetry of gold objects, we opted for a set of easily applicable solutions:

- Diffuse lighting to minimize reflections and white hotspots by means of translucent curtains [1].
- Shooting frames from multiple angles to mitigate the effect of reflections. The type of network developed is not limited to the classic type that is achieved by photographing the subject from multiple angles by rotating it on a circular table, but also by introducing additional photographs whose purpose is to fill in any occluded areas.
- Post-Processing algorithms for mesh recovery [26] of photogrammetric reconstruction including smoothing surfaces, and sharp creases enhancement (Figure 15(a) and (b)).
- Fitting of polygonal geometric primitives with respect to high detail mesh reference and assembly within geometric modeling environment (Figure 15(c) and (d)).

2.3.2 Parameterization, Texturing, Interaction. The use of quad-dominant mesh primitives allows for much faster parameterization than models formed from triangles [9], which among other things show limited adherence to the features of geometrically regular models such as those in the collection under consideration. Due to the low quality of the meshes at the metal areas it is not possible to perform a baking of the normals from high-poly to low-poly model, and therefore we opted for a technique that is very common in the realization of 3D assets that fall under the so called "hard-box modeling" type and that is the use of the low-poly model as if it were a high-poly. In fact, the rendering of round edges can also be achieved using bevel shaders, to avoid generating explicit geometry [49]. Therefore, it is possible to avoid introducing details on the edges through beveling commands, but at the same time to store this fictitious geometry on a normal map applied to the final model. This solution helps to give the edges of the metal areas a realistic appearance, thus saving both modeling time and hardware resources (Figure 16).

Fig. 16. Different physically based textures applied to the microscope model and final rendering. Screenshots of the application while exploring the digital model (image by G. Fracascia).

The general workflow, focused on reproducing gold elements, is generally centered around a high value for the metallic parameter and a yellow-orange color for the base color; in addition to this, roughness maps play a very important role in obtaining nonhomogeneous reflections, particularly in difficult-to-access areas of the model such as fillets, undercuts, and damaged areas. As in the case of the *Orcinus Citoniensis*, the interactive application was developed inside Epic Games Unreal 4.27. In part, work on the shaders was reused to enable visual isolation of elements inside the instrument (such as the lens system that is occluded by the metal protective caps, Figure 16).

3 Physical Interaction with the Developed Models

In the context of developing interactive visualization solutions for museums and exhibitions, a methodology was implemented to design high-resolution kiosks aimed at enhancing the enjoyment of digitized works, to navigate them through common gestures on touch surfaces or proximity sensors. It should be noted that the kiosk presented as follows was designed specifically for the *Annunciation* case study at the express request of the museum in San Giovanni Valdarno, to evaluate how the digital replica could enhance the original exploration when used alongside the physical work.

The interactive kiosk proposed is a flexible, scalable, and adaptable tool catering to different purposes and visitor profiles and, even though presented in this article for the *Annunciation* only, it could be versatile enough to be applied to all the case studies. The introduction of interactive installations within museums represents a significant

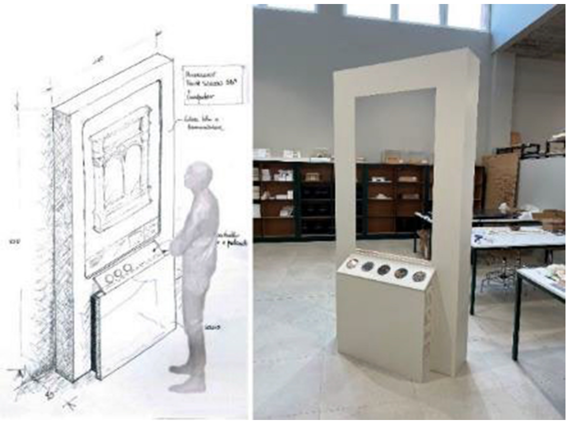


Fig. 17. Conceptual design and kiosk's implementation: an initial design sketch illustrating the envisioned kiosk layout and features, and a picture showing the actual kiosk being built, demonstrating how the concept is translated into physical form (sketch by F. I. Apollonio and image by S. Garagnani).

evolution in the museum experience, allowing visitors to explore content in ways that deepen their understanding and appreciation of the displayed works. This approach integrates interaction and technical components to create an engaging and authentic visitor experience. The interactive kiosk designed for the *Annunciation's* 3D replica not only offers a detailed enjoyment of Cultural Heritage but also fosters a personal connection between the user and the artwork through a combination of digital and physical interaction.

3.1 Kiosk Description and Development

Particularly effective is the comparison between the real *Annunciation* and the replicated one in the *AnnunciatiOn App*, as visitors can interact with the masterpiece in a personal way, "touching" its virtual replica to establish a more intimate relationship with the object. Consequently, the idea was adopted to run the *AnnunciatiOn App* on a dedicated kiosk, made of wood, that recalls the frame around the original painting. This kiosk was placed in the same room, close to the original artwork, intensifying the interactive experience.

Its structure has been designed to ensure both functionality and context-compatible aesthetics. It has a vertical shape that accommodates the touch screen, as well as containing all the necessary hardware to run the application. It was designed as a vertical frame to house the touch screen and to host all the hardware needed to run the app, including a workstation hidden behind a removable panel to facilitate maintenance operations. The dimensions of the kiosk were set at 110 × 220 × 49 cm. Special focus has been placed on ergonomics and accessibility, with the integration of a physical keyboard positioned below the vertical screen (Figure 17). This physical keyboard offers users direct and intuitive access to the different sections of the guided tour.

3.2 Interaction Model

The different manifestations of digital approaches and tools are currently a valuable support for museum configurations, especially when the connection of information is one of the main interpretative objectives of an exhibition. Digital solutions can lead visitors into complex collections through narrative itineraries that highlight logical relationships between various elements, which might not be clear at first glance [50]. In addition to this, the use of 3D digital representations of objects can generate different kinds of layouts, linking several museums works through shared intangible elements, which can be highlighted and described in a virtual context [51].

The synergy between digital and physical interaction is the very essence of the experience offered by the interactive kiosk. This fusion of approaches allows visitors to fully immerse themselves in the cultural heritage on display, creating a deep and authentic involvement. Through digital interaction, visitors can explore previously invisible details of the artwork and access contextual information in a dynamic way, while physical interaction offers a tactile and tangible element that amplifies the emotional connection with the artwork itself.

The museum experience should be a connection between the visitor and what they are seeing [52]. In the case of our interactive kiosk, the aim is precisely to facilitate this connection through the synergetic use of digital and physical interactions.

The physical interaction through soft-touch buttons represents a tangible link to virtual artwork. The illuminated buttons, with their visual effect, invite visitors to explore and discover the different sections of the guided tour, offering an immersive experience that goes beyond mere passive viewing.

3.3 The Development of the Interactive Controllers

A hand button panel was placed under the vertical screen to allow users to access easily and directly each of the five sections of the guided tour (Figure 18).

An Arduino board, an open source electronic platform, was used as the microcontroller, to detect the presence of the hand on the buttons, enabling control over various "scenes" during the guided tour. It is the most widely used solution for developing interactive controllers in museum exhibitions [53]. The choice fell on Arduino because it is a low-cost board, it is a small device suitable for being embedded in common objects to make them interactive [54], it is multiplatform, and the programming environment (IDE) is easy to use. Specifically, the Leonardo microcontroller requires a voltage of 5 V, and is therefore easily powered by a standard USB port.

The use of an ATmega32u4 (Leonardo) microcontroller enabled the driving of illuminated soft-touch buttons. These buttons, when activated, emit a flashing white light that visually indicates the corresponding section of the tour. The basic operation of the program is related to the "keyboard" library, which allows 32u4 or SAMD micro-based boards to send key sequences to a connected computer via the micro's native USB port. These sequences are interpreted via USB by Unity as a virtual keyboard and command the various sections of the tour. For example, when the first physical soft-touch button is pressed, a keyboard character "A" is sent via the microcontroller to the Unity app, which activates the first content animation related to the first part of the guided tour.

Each button consists of a 3D printed ring and a "NeoPixel" strip with WS2812 RGB LEDs, which illuminate a transparent methacrylate disc. In addition, two-pin vetronite plates, a material often used for circuit boards, are integrated into the electronic controller, turning them into sensors capable of sensing the electrical capacity of human hands. The buttons act as antennas and, through careful calibration, it was possible to interact with the model when the palm of a hand is in the vicinity of the circular element.

To distinguish the different stages of the guided tour, details of the work were used. Specifically, a high-quality photographic paper print of a portion of the work was placed between the transparent methacrylate disc and the vetronite plates, so that the user could easily associate the animated content on the screen and the correlation on the physical keyboard.

The versatility of the application is underlined by its ability to adapt also to scholars: In fact, some specific functions can also be performed via traditional devices. For instance, pressing the space key on a connected keyboard will change the interface out of kiosk mode to allow exploration of the painting via a common pointing device. The video resolution, usually set to 4K during exposure, is automatically adjusted to the maximum values provided by the connected hardware, if available. In this way, the application can comply with multiple hardware requirements in different exhibition contexts.

This physical interface was developed through the adaptation of an ATmega32u4 (Leonardo) microcontroller, which manages five illuminated soft-touch buttons that visually indicate the reference section through a flashing white light when activated. Each button consists of a 3D-printed ring made of white PLA, around which a

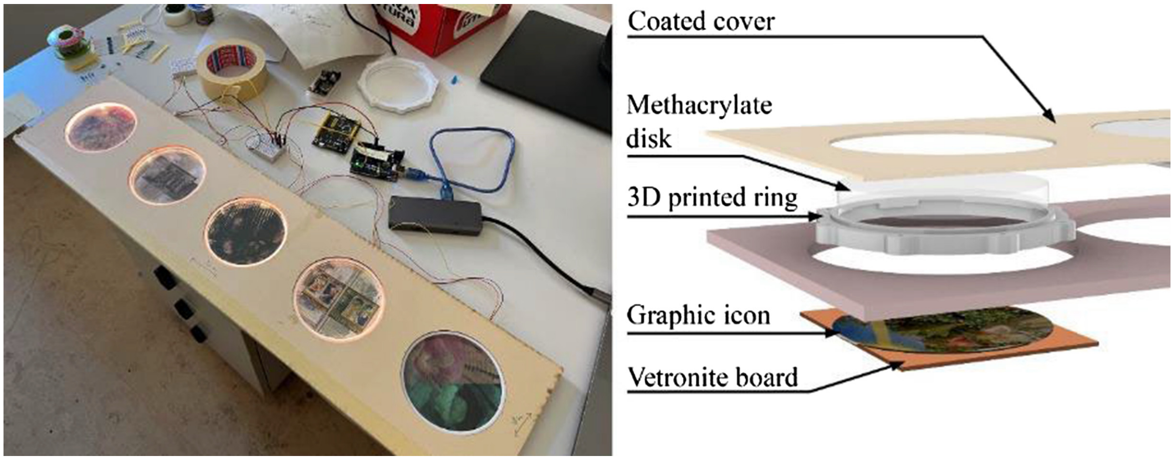


Fig. 18. From left, the physical capacitive keyboard with customized proximity button; on the right, the corresponding schematic. (Image by L. Barbieri and exploded view schematic by L. Barbieri.)

"NeoPixel" strip with five WS2812 RGB LEDs is positioned to illuminate a transparent methacrylate disc. In addition, several vetronite plates have been soldered on.

4 Discussion and Conclusion

In this article, various digitization and representation problems have been exposed: from those with refined custom-made tools including high-end reflex cameras, to those with low-cost standard approaches and devices. Geometric data processing procedures have been illustrated which prove to be advantageous for lightening the models and, at the same time, maintaining the original geometric detail by integrating widespread modeling techniques in the CGI (normal maps) and image filtering systems coming from the photogrammetric field (color-to-grey filter). Faithfully replicating the color and surface appearance of surfaces characterized by complex optical behavior, such as gold leaf, while remaining an extremely difficult task, can benefit from the advantages of specially designed lighting rigs and color processing techniques. The greater the level of complexity and the fidelity of documentation of the artworks, the greater the skills of the operators and consequently the financial effort connected to the digitization operation. Nonetheless, the average quality of draft models obtained with low-cost techniques can be compensated by geometric modeling techniques together with material and texture authoring applications. Just think of the huge effort of important software houses in integrating AI-based solutions in image manipulation to obtain sets of physically reliable textures in reproducing the optical properties of conductive and dielectric materials. But if on the one hand, the creation of digital replicas, more or less accurate, is a theme that has now entered the collective imagination (evidenced by the use and sometimes inappropriate use of phrases such as digital twins) on the other the creation of *ad-hoc* installations represents a significant obstacle, especially for smaller museums with limited budgets. The need to work on the code or in any case on blueprint (VPL) type systems of programs with a steep learning curve as happens for engines represents an important cost for these smaller art centers [55]. For this reason, it is essential to provide for the possibility of reusing kiosks that host touchscreen devices and the scalability of applications on portable devices such as smartphones and tablets which, among other things, allow you to enjoy additional online content on Web sites as Sketchfab [56].

The final step of the workflow involves RTR of artwork, which has proven to be a pivotal component in enhancing both the exhibition experience and scholarly research (Figure 19). The case studies presented demonstrate that game engines can achieve the necessary level of perceptive accuracy required for museum exhibitions, enabling scholars to explore artworks with diverse characteristics even in the absence of the originals, thus uncovering

Fig. 19. The exhibition “Masaccio e Angelico. Dialogo sulla verità nella pittura” (17 September 2022–5 February 2023) at the Museum of the Basilica of Santa Maria delle Grazie, in San Giovanni Valdarno (Arezzo, Italy). Physical and perceptual limitations are overcome through the digital interactive kiosk (images by S. Garagnani).

new insights. Both Unity and Unreal Engine were tested due to their widespread use. Unity proved to be highly effective in terms of versatility and portability, making it suitable for various devices commonly used in exhibits, such as touch monitors and customized kiosks. On the other hand, Unreal Engine excelled in creating immersive experiences within gaming environments. This dual approach underscores the potential of game engines in transforming the visualization and study of Cultural Heritage.

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Author Statement

The present research is the result of the combined work of the authors across diverse contribution roles. In writing the original draft, Fabrizio I. Apollonio was responsible for Sections 1 and 4; Michele Zannoni and Luca Barbieri for Section 4; Filippo Fantini for Sections 2.1 and 2.3; and Simone Garagnani for Section 2.1. All the presented results are derived from a collaborative synthesis of their work.

References

[1] Marco Gaiani, Fabrizio Ivan Apollonio, and Filippo Fantini. 2020. Una metodología inteligente para la digitalización de colecciones museísticas. *EGA Expresión Gráfica Arquitectónica* 25, 38 (2020), 170–181. DOI: https://doi.org/10.4995/ega.2020.12281

[2] Marco Gaiani, Fabrizio Ivan Apollonio, and Filippo Fantini. 2019. Evaluating smartphones color fidelity and metric accuracy for the 3D documentation of small artifacts. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* XLII-2/W11 (2019), 539–547. DOI: https://doi.org/10.5194/isprs-archives-XLII-2-W11-539-2019

[3] Filippo Fantini, Marco Gaiani, and Simone Garagnani. 2023. Knowledge and documentation of renaissance works of art: The replica of the "Annunciation" by Beato Angelico. *Int.* Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLVIII-M-2-2023 (2023), 527–534. DOI: https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-527-2023

[4] Pedro Manuel Cabezos-Bernal, Pablo Rodriguez-Navarro, and Teresa Gil-Piqueras. 2021. Documenting paintings with gigapixel photography. *J. Imaging* 7, 8 (2021), 156. DOI: https://doi.org/10.3390/jimaging7080156

[5] Pedro Manuel Cabezos-Bernal, Pablo Rodriguez-Navarro, and Teresa Gil-Piqueras. 2021. Documenting paintings using gigapixel SfM photogrammetry. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* XLVI-M-1-2021 (2021), 93–100. DOI: https://doi.org/10.5194/isprs-archives-XLVI-M-1-2021-93-2021

[6] Jonathan Cohen, Marc Olano, and Dinesh Manocha. 1998. Appearance-preserving simplification. In *Proceedings of the 25th Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '98)*. ACM, New York, NY, 115–122. DOI: https://doi.org/10.1145/280814.280832

[7] Xianfeng Gu, Steven J. Gortler, and Hugues Hoppe. 2002. Geometry images. In *Proceedings of the 29th Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '02)*. ACM, New York, NY, 355–361. DOI: https://doi.org/10.1145/566570.566589

[8] Stephen Hill, Stephen McAuley, Laurent Belcour, Will Earl, Niklas Harrysson, Sébastien Hillaire, Naty Hoffman, Lee Kerley, Jasmin Patry, Rob Pieké, et al. 2020. Physically based shading in theory and practice. In *Proceedings of the ACM SIGGRAPH 2020 Courses (SIGGRAPH '20)*. ACM, New York, NY, Article 11, 1–12. DOI: https://doi.org/10.1145/3388769.3407523

[9] Fabrizio Ivan Apollonio, Filippo Fantini, Simone Garagnani, and Marco Gaiani. 2021. A photogrammetry-based workflow for the accurate 3D construction and visualization of museums assets. *Remote Sensing* 13, 3 (2021), 486. DOI: https://doi.org/10.3390/rs13030486

[10] Marco Gaiani, Simone Garagnani, and Michele Zannoni. 2022. Displaying Dante's Divine Comedy miniated manuscripts in exhibitions. *SCIRES-IT* 12, 1 (2022), 77–94. DOI: https://dx.doi.org/10.2423/i22394303v12n1p77

[11] Daniela Petrelli, Alessandro Soranzo, Luigina Ciolfi, and John Reidy. 2016. Exploring the aesthetics of tangible interaction: Experiments on the perception of hybrid objects. In *Proceedings of the TEI '16: 10th International Conference on Tangible, Embedded, and Embodied Interaction (TEI '16)*. ACM, New York, NY, 100–108. DOI: https://doi.org/10.1145/2839462.2839478

[12] Daniela Petrelli and Sinead O'Brien. 2018. Phone vs. tangible in museums: A comparative study. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, New York, NY, Paper 112, 1–12. DOI: https://doi.org/10.1145/3173574.3173686

[13] Ruggero Pintus, Kazim Pal, Ying Yang, Tim Weyrich, Enrico Gobbetti, and Holly Rushmeier. 2016. A survey of geometric analysis in cultural heritage. *Comput. Graph. Forum* 35 (2016), 4–31. DOI: https://doi.org/10.1111/cgf.12668

[14] S. Garagnani, R. D'Ugo, A. Lupi, B. Martini, M. Salvucci, M. Susta, M. Tombolato, and R. Barsanti. 2022. Visual perception and cognition by the means of interactive digital replicas of museum artifacts: Leonardo da Vinci's drawings as if they were in visitors' hands. *Heritage* 6 (2023), 1–25. DOI: https://doi.org/10.3390/heritage6010001

[15] Anna Ottani Cavina. 1988. *Palazzo Poggi da dimora aristocratica a sede dell'Università di Bologna*. Nuova Alfa, Bologna, Italy.

[16] Carlo Sarti. 2012. 1860-2010: 150 years of the Capellini Museum (University of Bologna), the most ancient Italian Geo-Paleontological Museum. *GeoActa* 11 (2012), 1–26.

[17] Fabio Remondino. 2011. Heritage recording and 3D modeling with photogrammetry and 3D scanning. *Remote Sens.* 3, 6 (2011), 1104–1138. DOI: https://doi.org/10.3390/rs3061104

[18] Eugenio Bertozzi. 2020. *Augusto Righi and the Intuition of the Experiment. Il Nuovo Saggiatore36 (5-6)*. Societa Italiana di Fisica. Bologna, Italy, 51–60.

[19] Carl Brandon Strehlke. 2022. *Masaccio e Angelico. Dialogo sulla verità nella pittura*. Magonza, Arezzo, Italy.

[20] Johannes Kopf, Matthew Uyttendaele, Oliver Deussen and Michael F. Cohen. 2007. Capturing and viewing gigapixel images. In *Proceedings of the ACM SIGGRAPH 2007 Papers*. ACM, New York, NY, 93–103. DOI: https://doi.org/10.1145/1275808.1276494

[21] Robert J. Woodham. 1989. Photometric method for determining surface orientation from multiple images. *Opt. Eng.* 19, 1 (1989), 139–144.

[22] D. Trenholme and S. P. Smith. 2008. Computer game engines for developing first-person virtual environments. *Virtual Reality* 12 (2008), 181–187. DOI: https://doi.org/10.1007/s10055-008-0092-z

[23] Michael J. Ziegler, Victor J. Perez, Jeanette Pirlo, Rachel E. Narducci, Sean M. Moran, Molly C. Selba, Alexander K. Hastings, Claudia Vargas-Vergara, Pavlo D. Antonenko, and Bruce J. MacFadden. 2020. Applications of 3D paleontological data at the Florida museum of natural history. *Front. Earth Sci.* 8 (2020), 1–20. DOI: https://doi.org/10.3389/feart.2020.600696

[24] Marco Gaiani. 2015. Modelli 3D e studi per un sistema conoscitivo dei portici di Bologna. In *I porti di Bologna, Architettura, Modelli 3D e ricerche tecnologiche*. Marco Gaiani (Ed.), Bononia University Press, Bologna, 1–200.

[25] Slizewski Astrid, Martin Friess, and Patrick Semal. 2010. Surface scanning of anthropological specimens: Nominal-actual comparison with low cost laser scanner and high end fringe light projection surface scanning systems. In *Quartär Yearbook for Ice Age and Stone Age Research, 57.* Verlag Dr. Faustus, Büchenbach, 179–187.

[26] Pierre Alliez, Giuliana Ucelli, Craig Gotsman, and Marco Attene. 2008. Recent advances in remeshing of surfaces. In *Shape Analysis and Structuring. Mathematics and Visualization*. L. De Floriani and M. Spagnuolo (Eds.), Springer, Berlin, 53–82. DOI: https://doi.org/10.1007/978-3-540-33265-7_2

[27] Hugues Hoppe. 1996. Progressive meshes. In *Proceedings of the 23rd Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '96).* ACM Press, New York, NY, 99–108.

[28] Marco Potenziani, Marco Callieri, Matteo Dellepiane, Massimiliano Corsini, Federico Ponchio, and Roberto Scopigno. 2015. 3DHOP 3D heritage online presenter. *Computers & Graphics*. 52 (2015), 129–141. DOI: https://doi.org/10.1016/j.cag.2015.07.001

[29] Josefina García-León, Paloma Sánchez-Allegue. Concita Peña-Velasco, Luca Cipriani, and Filippo Fantini. 2018. Interactive dissemination of the 3D model of a baroque altarpiece: A pipeline from digital survey to game engines. *SCIRES-IT Sci. Res. Inf. Technol* 8, 5 (2018), 9–76. Retrieved from http://dx.doi.org/10.2423/i22394303v8n2p59

[30] Wenzel Jakob, Marco Tarini, Daniele Panozzo, and Olga Sorkine-Hornung. 2015. Instant field-aligned meshes. *ACM Trans. Graph.* 34 (2015), 1–15. DOI: https://doi.org/10.1145/2816795.2818078

[31] Wallis Robert. 1976. An approach to the space variant restoration and enhancement of images. In *Proceedings of Symposium on Current Mathematical Problems in Image Scenes*. Naval Postgraduate School, Monterey, CA, 329–340.

[32] Marco Gaiani, Fabio Remondino, Fabrizio I. Apollonio, and Andrea Ballabeni. 2016. An advanced pre-processing pipeline to improve automated photogrammetric reconstructions of architectural scenes. *Remote Sensing* 8, 3 (2016), 178. DOI: https://doi.org/10.3390/rs8030178

[33] Jassim Happa, Tom Bashford-Rogers, Alexander Wilkie, Alessandro Artusi, Kurt Debattista, and Alan Chalmers. 2012. Cultural heritage predictive rendering. *Comput. Graph. Forum* 31, 6 (Sept. 2012), 1823–1836. DOI: https://doi.org/10.1111/j.1467-8659.2012.02098.x

[34] M. Magdy. 2022. Insights into the effect of UV radiation on paintings: A mini-review for the asset preservation of artworks. *Adv. Res. Conserv. Sci.* 3, 2 (2022), 46–54. DOI: https://doi.org/10.21608/arcs.2022.167664.1031

[35] Santiago Mayorga Pinilla, Daniel Vázquez, Antonio Álvarez Fernández-Balbuena, Carmen Muro, and Javier Muñoz. Spectral damage model for lighted museum paintings: Oil, acrylic and gouache. *J. Cult. Herit.* 22 (2016), 931–939. DOI: https://doi.org/10.1016/j.culher.2016.05.005

[36] A. Dhanda, G. Scarpa, S. Fai, and M. Santana Quintero. 2019. A workflow for geometric colour photography of painted surfaces. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* XLII-2/W11 (2019), 469–474. DOI: https://doi.org/10.5194/isprs-archives-XLII-2-W11-469-2019

[37] Roy S. Berns. 2001. The science of digitizing paintings for color-accurate image archives: A review. *J. Imaging Sci. Technol.* 45, 4, (Jul./Aug. 2001), 305–325.

[38] Marco Gaiani, Fabrizio Ivan Apollonio, and Andrea Ballabeni. 2021. Cultural and architectural heritage conservation and restoration: Which colour? *Coloration Technol*. 137 (2021), 44– 55. DOI: https://doi.org/10.1111/cote.12499

[39] Tomas Akenine-Möller, Eric Haines, and Naty Hoffman. 2018. *Real-Time Rendering*, 4th ed. Taylor & Francis, CRC Press, Boca Raton, FL. DOI: https://doi.org/10.1201/b22086

[40] David H. Eberly. 2015. *3D Game Engine Design: A Practical Approach to Real-Time Computer Graphics*. Taylor & Francis, CRC Press, Boca Raton, FL.

[41] Sebastien Lagarde. 2018. The High Definition Render Pipeline: Focused on Visual Quality. Retrieved April 25, 2020 from https://blogs.Unity.com/2018/03/16/the-high-definition-render-pipeline-focused-on-visual-quality/

[42] Brent Burley. 2012. Physically-based shading at Disney, course notes. In *Proceedings of the SIGGRAPH '12 Courses.* ACM, New York, NY, Article 10, 1–27.

[43] Claudia Doppioslash. 2018. *Physically Based Shader Development for Unity 2017.* Apress.

[44] Giovanni Verri, Satoko Tanimoto and Catherine Higgitt. 2010. Inks and washes. In *Italian Renaissance Drawings: Technical Examination and Analysis*. Janet Ambers, Catherine Higgitt, and David Saunders (Eds.), Archetype Publications, London, UK, 57–76.

[45] Brent Burley. 2015. Extending Disney's physically based BRDF with integrated subsurface scattering. In *Proceedings of the SIGGRAPH '15 Courses.* ACM, New York, NY, Article 22.

[46] Paul E. Dickson, Jeremy E. Block, Gina N. Echevarria, and Kristina C. Keenan. 2017. An experience-based comparison of unity and unreal for a stand-alone 3D game development course. In *Proceedings of the 2017 ACM Conference on Innovation and Technology in Computer Science Education (ITiCSE '17).* ACM, New York, NY, 70–75. DOI: https://doi.org/10.1145/3059009.3059013

[47] A. Ciekanowska, A. Kiszczak - Gliński, and K. Dziedzic. 2021. Comparative analysis of Unity and Unreal Engine efficiency in creating virtual exhibitions of 3D scanned models. *J. Comput. Sci. Inst.* 20 (2021), 247–253. DOI: https://doi.org/10.35784/jcsi.2698

[48] Simon Courtin, Sébastien Horna, Mickaël Ribardière, Pierre Poulin, and Daniel Meneveaux. 2019. Efficient rendering of rounded corners and edges for convex objects. In *Proceedings of the Advances in Computer Graphics*, Lecture Notes in Computer Science, 291–303.

[49] Balzani Roberto, Barzaghi Sebastian, Bitelli Gabriele, Bonifazi Federica, Bordignon Alice, Cipriani Luca, Colitti Simona, Collina Federica, Daquino Marilena, Fabbri Francesca, et al. 2023. Saving temporary exhibitions in virtual environments: The Digital Renaissance of Ulisse Aldrovandi. arXiv:2308.15920. Retrieved from https://arxiv.org/abs/2308.15920

[50] Parry Ross. 2010. *Museums in a Digital Age.* Routledge, London, UK.
[51] Laura Loredana Micoli, Giandomenico Caruso, and Gabriele Guidi. 2020. Design of digital interaction for complex museum collections. *Multimodal Technol. Interact.* 4, 2 (2020), 1–20. DOI: https://doi.org/10.3390/mti4020031
[52] Falk John Howard. 2009. *Identity and the Museum Visitor Experience.* Routledge, New York, USA.
[53] Alessandra Bosco, Silvia Gasparotto, and Michele Zannoni. 2019. Design processes for enhancing museums through the use of technology and the involvement of local communities. *Strateg. Des. Res. J.* 12 (2019), 261–275. DOI: https://doi.org/10.4013/SDRJ.2019.122.11
[54] Dimitropoulos Anastasios, Dimitropoulos Konstantinos, Kyriakou Angeliki, Malevitis Maximos, Syrris Stelios, Vaka Stella, Koutsabasis Panayiotis, Vosinakis Spyros, and Stavrakis Modestos. 2018. The Loom: Interactive weaving through a tangible installation with digital feedback. In *Digital Cultural Heritage.* M. Ioannides (Eds), Lecture Notes in Computer Science, Vol. 10605, Springer, Cham, 199–210. DOI: https://doi.org/10.1007/978-3-319-75826-8_17
[55] Bertollini Marina, Caramis Alessandro, D'Elia Marica, Rosaria M. Prisco, and Silvia Talice. 2019. Statistica sperimentale. *I percorsi museali in Italia nel 2015*. (Dec. 3, 2019). Retrieved September 8, 2023 from https://www.istat.it/it/archivio/236140
[56] Bertacchi Silvia, Bertacchi Gianna, and Luca Cipriani. 2022. Chiuro laboratory: Integration of workflows from digital survey to optimised 3D urban models for interactive exploration. *Appl. Geomat.* 14, Suppl 1 (2022), 131–150. DOI: https://doi.org/10.1007/s12518-020-00352-1

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