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Beyond the frame: a multifaceted approach to Cultural Heritage 3D models through levels of iconicity and user-centric visualization tools

This paper introduces a discussion on the visualization tools for digital replicas of objects belonging to the domains of historic architecture, archaeology, and art museum institutions.
Covering a range of artifacts, from ancient drawings to manuscripts, to paintings, to objects in museums' collections, the discussion spans from levels of iconicity related to 3D models to their presentation and visualization media.
Authors introduce some established experiences, inferred from real case studies showcased during real exhibitions, to show how digital artifacts can replicate existing objects for specific purposes, with high levels of iconicity.
The paper traces approaches in 3D model visualization, utilizing technologies such as Real-Time Rendering (RTR) and Virtual Reality frameworks. After a methodical acquisition of artworks to be replicated, the digital models are targeted to various stakeholders with interests in historical and artistic research, curation of museum exhibition, art restoration, or simple tourism visits. The way through which the artwork can be visualized, presenting different features each time, depends on their needs, from guided navigation of 3D models on laptop screens accompanied by explanatory texts, to free visualization through gestures on interactive high-definition touch screens. By employing high-resolution replicas mapped with gigapixel textures, even the minutest details can be observed.
This approach virtually places the artwork in the hands of the users, allowing them to appreciate its characteristics at a very high level of iconicity, also enhancing the narrative potential of digital replicas in museum exhibitions.

Keywords:
RTR representation; level of iconicity; Cultural Heritage visualization; museum tools for dissemination; fruition hardware for virtual exhibitions.

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INTRODUCTION: DIGITAL VISUALIZATION AND LEVELS OF ICONICITY

According to Meir and Tkachman [2018], iconicity is a relationship of resemblance between the two aspects of a sign: its form and its meaning. This is not a novel concept indeed. The sociologist and communication theorist Abraham A. Moles explains the iconicity as the degree of similarity between an image and the object that this image represents or, if preferred, the degree of realism of a drawing [Moles, 1972]. This remark covers one of the fundamental principles of drawing, established as a scientific discipline based on the analogy between the form of a sign and the concept it refers in our perception of the world [Bouissac, 1998].

In his work, Moles proposes a ranking divided into twelve levels of iconicity, to cover all the possibilities in image creation, ranging from *Abstraction 11*, the subject itself, to *Abstraction 0*, an implicit description by means of standard words or mathematical formulae [Moles & Janiszewski, 1990; Moles, 1981].

Today's digital modeling, as a progress in representation techniques, allows for a multitude of different approaches, according to which the computer reproduction of the world around us takes on the features of a three-dimensional copy or even a virtual prototype of what it is meant to represent [Losciale et al., 2012].

Currently, digital replication techniques have sufficiently matured to get closer and closer, even though not adherent, to the highest abstractions by Moles, both in terms of geometry and visual perception.

Digital replicas may convincingly replicate the original artworks under investigation, providing users with the sensation of having the authentic items at their disposal, replicating the true appearance even when examined from different viewpoints. [Gaiani et al., 2024]. Additionally, a comprehensive representation of knowledge is often depending on how it can be collected and presented through different media, taking advantage of their potential.

Initially rooted in conventional representation shaped by technical drawings or photographs, the visualization of works of art and its evolution led to contemporary digital representations that leverage emerging technologies, such as Real-Time Rendering (RTR) and Virtual or Augmented Reality frameworks [Barricelli et al., 2016; Pierdicca et al., 2016].

Thence, the challenge in utilizing these mediums lies in selecting the appropriate tool to achieve the desired levels of iconicity, conveying information embedded within digital replicas that must remain faithful to the original in many possible aspects. Each distinct technique or visualization tool introduces varying degrees of iconicity within the replicas, particularly when tailored to different potential end-users. The need of a high-grade perceptual replication is becoming crucial in the dissemination of objects belonging to the domains of historic architecture, archaeology, and museum institutions specialized in artworks [Petrelli, 2019].

In scientific literature, several papers were written over the years about digital methods applied to the preservation, documentation and understanding of collections dedicated to these fields, which historically count a consisting number of case studies related to the application of hardware and software dedicated to digital documentation [Giannakoupoulos et al., 2021].

The perceptual accuracy of computer-generated reproductions holds importance, particularly in presentations artifacts that may not be easily accessible in their original form. Therefore, guaranteeing a digital replica that accurately mimics the original is crucial for communicating information to both exhibition visitors and scholars, especially when the artworks are preserved under strict conditions that restrict access for observation and analysis, such as ancient drawings kept often in storage for safe preservation (Figure 1).

To address this challenge, this paper focuses on introducing visualization techniques and hardware solutions aimed at achieving a level of iconicity in which a digital replica of an artwork can successfully substitute the original, or facilitate a

Fig. 1 - Digital replica of the "Landscape" drawing (recto, inv. 8P) by Leonardo da Vinci (1473), with the original masterpiece hosted at Le Gallerie degli Uffizi, GDSU in Florence and often kept in safety with extremely limited access.

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<table>
<tr><th colspan="2">Interaction</th><th>Software</th><th colspan="2">Visualization device</th><th>Dimension</th><th>Iconicity</th><th>Applicability</th></tr>
<tr><td rowspan="2">Mouse + Keyboard</td><td></td><td>Word processing</td><td rowspan="7">Monitor</td><td rowspan="6">Mono</td><td rowspan="4">2D</td><td>0</td><td>Text</td></tr>
<tr><td rowspan="3">Tablet + Pen</td><td>Tools for office tasks</td><td>1</td><td>Schemes, graphs, diagrams</td></tr>
<tr><td rowspan="2">3 buttons mouse + Keyboard</td><td>Editing of 2D pictures</td><td>2</td><td>Images</td></tr>
<tr><td>Geometric modeling software</td><td>3</td><td>Formulae, sociograms</td></tr>
<tr><td>Mouse 4D Joystick</td><td rowspan="2">Touch / Gestures</td><td rowspan="2">BIM modeling software</td><td rowspan="8">3D</td><td>4</td><td>Drawings</td></tr>
<tr><td rowspan="2">Touch screens</td><td>5</td><td rowspan="2">Small-scale objects, study, individual verification</td></tr>
<tr><td rowspan="6">VR stereo goggles + tracking</td><td rowspan="4">VR Software</td><td rowspan="6">Stereo</td><td>6</td></tr>
<tr><td rowspan="3">Wand</td><td>Projection tables</td><td>7</td><td>Medium-sized models, possibility of collaborative interaction</td></tr>
<tr><td>Portable displays</td><td>8</td><td>Large real-scale models, territory, cultural heritage</td></tr>
<tr><td>CADWall CAVEs</td><td>9</td><td>Reconstructions of whole environments, interiors</td></tr>
<tr><td rowspan="2">Haptic gloves</td><td rowspan="2">RTR game engines</td><td rowspan="2">HMD</td><td rowspan="2">10</td><td>Full environments, Augmented reality, interaction with other users</td></tr>
<tr><td>Prototypes, perceptual 3D reconstructions close to the original</td></tr>
<tr><td colspan="6"></td><td>11</td><td>Real object</td></tr>
</table>

Table 1 - Different levels of iconicity, following the scheme by A. Moles, and their possible related software/hardware implementation, classified to identify their applicability and their immersivity degree in the digital domain.

more informed exploration by first-time observers, perhaps with the opportunity to compare it with its original if present [Garagnani et al., 2023]. This can reasonably happen spanning at different scales, from ancient drawings to paintings, to physical artifacts to architectural parts.
The presented results, both implemented in terms of software and hardware tools, are the outcomes of years of experimental developments carried out during several research activities often ending in museum exhibitions [Apollonio et al., 2021; Gaiani et al., 2019]. In fact, as computers have become efficient enough to process huge quantities of data, the complex relationships between digital replicas and real artefacts encourage new thinking categories, different and more powerful than those traditionally adopted in exhibition design for museums.
Consolidated methods and related solutions are introduced following selected case studies, to prove how digital artifacts behave as substitutes for real objects for certain purposes, following a comprehensive pipeline developed by the authors and spanning from the data acquisition to the interactive presentation through different devices targeted to different users' profiles.

INTERACTION DEVICES AND THEIR ICONICITY

To identify the optimal tools to be used in the visualization of digital replicas, Mauro Ceconello proposed in 2003 a scheme to classify the various types of hardware devices and software applications involved in managing 3D models [Ceconello, 2023]. The scheme was produced beginning from the taxonomy based on the levels of iconicity by Moles [Moles, 1981].
The Ceconello's classification, which mainly related interaction tools to visualization modes, was further refined, integrated, and revised for this paper, as expressed in Table 1, which basically updates the original one.
As stated, the perceptivity level grows as the applied technology does: considering at first the scale of the object of interest, it is possible to choose the best tool or technology to use to interact with its digital dual. This is an important feature for example in the definition of replicas' features meant for museum's collections, where the perceptivity of the replicated object can influence its usability towards visitors, scholars, curators, restorers, or other figures involved.
Usually, mice and keyboards are the traditional tools to interact with 3D models using laptops and desktop PCs, limiting nevertheless the interaction through a constrained mediation very different from the natural manipulation of real objects. The advent of tablets and smartphones led to the

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Fig. 2 - Mobile computing and a 3D model of a medieval manuscript visualized on a tablet PC (Microsoft Surface Go 2).

wide diffusion of touch screens, which introduced gestures that evolved the ability to manipulate, explore and navigate replicas especially of small-scale objects such as ancient drawings or manuscripts (Figure 2). Also, as interest in stereoscopic display devices that are increasingly less cumbersome for end users has grown, there has been a push towards abandoning 2D screens for representing spatial objects.
These devices can be seamlessly integrated into museum exhibits through interactive kiosks strategically placed throughout galleries, allowing visitors to access additional information, audio guides, and multimedia content related to displayed artworks.
Moreover, dedicated mobile applications can be developed, offering tailored experiences such as augmented reality tours, interactive maps, immersive audioscapes and curated digital galleries accessible via smartphones and tablets (Figure 3).

NEW PARADIGMS FOR PERCEPTUAL ACCURACY OF 3D REPLICAS

Dynamic visualization plays a crucial role in enhancing the interactive engagement with a digital replica. While conventional devices aim to display three-dimensional objects on two-dimensional screens in form of simple 3D models (i.e. 3D viewers on computer's screens), a shifting trend towards wider and more immersive systems enabled by gestures on touchscreens can be observed (Figure 4). In fact, touch screens can be easily incorporated into exhibition kiosks, enabling visitors to interact with digital replicas rather than the usual passive observation of protected originals, zooming in on details, and exploring supplementary multimedia contents, thereby enriching their overall experience. This trend is gaining momentum since the Covid-19 pandemics, during which many museum paradigms were forced to change [Querci et al. 2021].
However, the natural interaction per se is not sufficient to grant the perceptual accuracy necessary to substitute an original with a credible digital replica. The solution lies in the replication of the artworks' surface characteristics (i.e. color fidelity, light interaction behaviors typical for each of the materials employed, proper representation scale in visualization, correct shape definition), which can be reached with:

- a fine reproduction of the appearance for the artworks investigated, in terms of multiscale structures;
- the implementation of a pipeline for the accurate color reproduction starting from consolidated then improved methods [Akenine-Moller et al., 2018; Gaiani et al., 2018];
- the authoring of a navigation environment based on common gestures for multiple platforms, also targeted to VR devices.

The accurate modeling of the multiscale structures mentioned in step 1 is crucial for defining the behavior of materials [Motoyoshi et al., 2016; Ludwig & Meyer, 2016] and, consequently, their perception and reproduction in steps 2 and 3.
To reach a perceivable high level of iconicity, an artwork must be reproduced in terms of:

- *macrostructure*, which defines the overall shape of the object,
- *mesostructure*, composed of elements still visible to the naked eye but typically not con-

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sidered constitutive of the overall shape,

- *microstructure*, which determines the orientation of light reflection. It is typically considered to be made of microscopic facets orders of magnitude smaller than the resolution of the human eye.

In Figure 5, a practical example of the outcomes of the multiscale replication is represented, with reference to the parchment of a manuscript: the macrostructure represents the parchment's general shape, the mesostructure gives the features of inks and irregularities in the surface, while the microstructure improves the behaviors to light of the details like the gold foil's specularity and the general translucence.

The outcome of the whole solution extends beyond mere rendering, offering users to deeply examine the artwork's surface details from various perspectives and under diverse lighting conditions, in a dynamic way.

Through high-resolution image zooming (often relying on Gigapixel imaging techniques), users can scrutinize specific features, adjust lighting effects, and explore different sections of drawings, paintings, or manuscripts, through Graphic User Interfaces embedded into the visualization environment and mounted in kiosk installations (Figure 6). Hardware necessary for the experience may be differentiated according to the users targeted; a scholar may want to explore the artifact with a traditional laptop computer, keeping the ability to get into the details, while a museum's visitor could be interested in having a guided tour through the most relevant points of interest on a dedicated kiosk, and finally a restorers could be interested in checking preservation states through a more practical mobile device.

This way, the resources necessary for the best visualization experience may be tailored upon specific goals and needs, from workstation-grade desktop systems for advanced usage to mid-range tablets for simple visualization and personal guided tours or VR portable devices, such as Oculus Go goggles for example.

The focus on details, with annotations, or re-

Fig. 3 - Stereoscopic devices to explore 3D models through an immersive experience. A smartphone placed into a visor with lenses (left), and a Meta Oculus Go device (right).

Fig. 4 - A 4k resolution, 55 inches touchscreen to explore 3D replicas of ancient drawings (left) and a tablet to improve the knowledge on artworks (right) using simple gestures (exhibit Leonardo, Anatomia dei disegni [Reloaded], Museo Leonardiano in Vinci, 2023).

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Fig. 5 - The outcomes of the accurate 3D modeling of artworks and their materials following a pipeline able to digitize at different scales (Manuscript n.589, “Divina Commedia con chiose in volgare”).

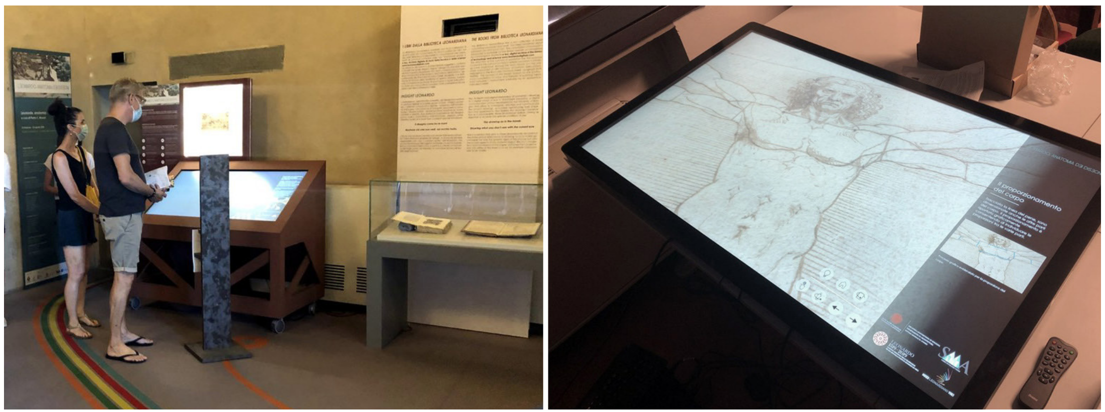

Fig. 6 - The exploration of a 3D model on a touch screen with a GUI meant to navigate through its details (exhibit Leonardo, Anatomia dei disegni [Reloaded], Museo Leonardiano in Vinci, 2023).

marks for analysis and exploration for all of them is much more comprehensive, provided that the models are perceptually reliable and possess a level of iconicity capable of rendering them almost virtually indistinguishable from the originals (Figure 7). This paradigm of usage can be imagined as having the artwork in one’s hands.

THE APPLICABILITY TO REAL CASE STUDIES

Ancient drawings, medieval manuscripts, Renaissance paintings, and artifacts from real museum collections served as case studies for testing the implemented method to reach the target level of perceived iconicity. These studies followed data acquisition campaigns, which almost employed custom-made software applications and hardware tools built for the purpose, as outlined in previous scientific publications [Apollonio et al., 2021; Gaiani et al., 2021; Gaiani et al., 2020; Apollonio et al., 2023]. The case studies upon which the notes on iconicity for this paper were prepared consisted in famous drawings by Leonardo da Vinci, spanning from 1473 to c. 1510-15, the *Annunciation* painting by Beato Angelico, dated 1430-32 in San Giovanni Valdarno, 3 pages (1, 69 and 137) from the Manuscript n.589, *Divina Commedia con chiose in volgare (Dante Lambertino)*, in Bologna, and a porcupinefish undergone to taxidermy treatment gathered by the naturalist Ulisse Aldrovandi, a specimen belonging to the Sistema Museale di Ateneo (SMA) in Bologna. Further details on these case studies are summarized in Table 2, in which the software and hardware tools used to interact with them with the highest level of iconicity are listed, together with the real exhibitions during which they were presented to a wider audience. The 3D models authored, and their level of iconicity, were extensively tested by scholars specialized in the respective research fields of the objects replicated. The listed 3D models were generated to reproduce the different structures of the surfaces of the original pieces (in terms of depth and surface normal) promoting the concept of “total appearance” [Berns et al., 2012]. The solution

Case study and location	Size of the artwork	Visualisation software developed	Interaction devices adopted	Reference museum exhibition
Leonardo da Vinci, "*Landscape*", 1473, recto: pen and iron-gall inks, lead point, blind point on paper; verso: pen, iron-gall inks, black, and red chalk, lead point, blind point on paper, Florence, Le Gallerie degli Uffizi, GDSU, inv. 8P.	194 x 285 mm	Interactive touch-based visualizer (based on customized RTR Engine: Unity 3D version 2018.4.31)	Touch screen 4K (3840x2160 px), 55 inches, driven by Nvidia Quadro P4000 (8 GB VRAM) GPU. Laptop PC release running on Apple MacOS and Microsoft Windows systems, with traditional keyboards and mice.	"Leonardo in Vinci. At the origins of the Genius", 15 April 2019 - 06 January 2020, Museo Leonardiano in Vinci, Castello dei Conti Guidi. Curated by R. Barsanti.
Leonardo da Vinci, "*Study of various buildings in perspective (study for the background of the Adoration of the Magi)*", around 1481, metal point, reworked with Pen and iron-gall ink, diluted iron-gall brush and ink, partially oxidized white gouache highlights (basic lead carbonate), stylus and compass on light brown prepared paper, Florence, Le Gallerie degli Uffizi, GDSU, inv. 436 E.	164 x 290 mm			
Leonardo da Vinci, "*Study of proportions of the human body known as The Vitruvian Man*", around 1490, metal point, pen, and iron-gall ink, watercolor ink touches, stylus on white paper, Venice, Gallerie dell'Accademia, Gabinetto dei Disegni e delle Stampe, inv. 228.	345 x 246 mm			
Leonardo da Vinci," *Two mortars launching explosives*", around 1485 (or shortly after), traces of black pencil (?), stylus tip, pen, and iron-gall ink, diluted ink, and watercolor with reworking on the right side, Milan, Veneranda Biblioteca Ambrosiana, Codex Atlanticus, f. 33.	219 x 410 mm	Interactive touch-based visualizer (based on customized RTR Engine: Unity 3D version 2019.4.27).	Touch screen 4K (3840x2160 px), 55 inches, driven by Nvidia Quadro P1000 (4 GB VRAM) GPU. Mobile tablet MS Surface Go 2, 12.4 inches, driven by Intel UHD Graphics 615 GPU. Laptop PC release running on Apple MacOS and Microsoft Windows systems, with traditional keyboards and mice.	"Leonardo, Anatomia Dei Disegni [Reloaded]" 16 April 2022 - 31 March 2023 Museo Leonardiano in Vinci, Castello dei Conti Guidi Curated by P. C. Marani, R. Barsanti, F. I. Apollonio, M. Gaiani.
Leonardo da Vinci, "*Fortress with a square plan, with very high scarp wall and concentric layout, with corner towers and grandiose ravelin in front*", 1507 or later, pen and iron-gall ink on black pencil, Milan, Veneranda Biblioteca Ambrosiana, Codex Atlanticus, f. 117.	131-207 x 436 mm			
Leonardo da Vinci, "*Two studies of legs, one seen from the side with the pelvis and belly, the other from the front*", c. 1506-08, red chalk retraced with sepia ink on red prepared paper, Milan, Veneranda Biblioteca Ambrosiana, Cod. F 263 Inf 84.	200 x 148 mm	Interactive touch-based visualizer (based on customized RTR Engine: Unity 3D version 2022.2.10).	Touch screen 4K (3840x2160 px), 55 inches, driven by Nvidia Quadro P1000 (4 GB VRAM) GPU. Mobile tablet MS Surface Go 2, 12.4 inches, driven by Intel UHD Graphics 615 GPU. Laptop PC release running on Apple MacOS and Microsoft Windows systems, with traditional keyboards and mice.	"Il Disegno Anatomico di Leonardo al Tempo del Salvator Mundi" 24 June 2023 - 30 June 2024 Museo Leonardiano in Vinci, Castello dei Conti Guidi Curated by P. C. Marani, R. Barsanti, M. Gaiani.
Anonymous Milanese (Francesco Melzi?), "*Anatomical studies of the muscles in the legs, with a study of a male figure seen from behind and the head and torso of a male figure*", c. 1510-13, red chalk superimposed with pen and sepia ink, black chalk, Milan, Civico Gabinetto dei Disegni, Castello Sforzesco, inv. Au. B 1359.	196 x 198 mm			
Anonymous Milanese, "*Standing male nude, male nude in profile and satyr (or Pan?) with lion*", c. 1510-15, three different fragments of paper glued together on a support, red chalk of three different types, Milan, Veneranda Biblioteca Ambrosiana, Cod. F 263 Inf 70.	140 x 148 mm (overall)			

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Case study and location	Size of the artwork	Visualisation software developed	Interaction devices adopted	Reference museum exhibition
Beato Angelico (Giovanni da Fiesole), the "*Annunciation*", c. 1430-40, egg tempera and gold foil on wood panels, Museo della Basilica di Santa Maria delle Grazie, San Giovanni Valdarno.	2380 x 2340 mm (overall)	Interactive touch-based visualizer (based on customized RTR Engine: Unity 3D version 2020.3.14) Keyboard soft touch interface: ATmega32u4	Touch screen 4K (3840x2160 px), 55 inches, driven by Nvidia GeForce RTX 3060 (12 GB VRAM) GPU. Physical soft-touch keyboard driven by an ATmega32u4 microcontroller with 5 soft-touch buttons made of a 3D printed ring around which was placed a NeoPixel strip with 5 RGB WS2812 LED diodes, to illuminate a transparent methacrylate disc. Laptop PC release running on Apple MacOS and Microsoft Windows systems, with traditional keyboards and mice.	Masaccio e Angelico. Dialogo sulla verità nella pittura" Museo delle Terre Nuove and Museo della Basilica di Santa Maria delle Grazie in San Giovanni Valdarno. Curated by M. Martini, D. Parenti, C. B. Strehlke, V. Zucchi
Manuscript n.589, "*Divina Commedia con chiose in volgare (Dante Lambertino)*", Biblioteca Universitaria di Bologna, Alma Mater Studiorum - University of Bologna, pages 1, 69 and 137.	273 x 187 mm	Interactive touch-based visualizer (based on customized RTR Engine: Unity 3D version 2020.3.14)	Touch screen 4K (3840x2160 px), 55 inches, driven by ASUS Phoenix Radeon RX 550 (4 GB VRAM) GPU. Laptop PC release running on Apple MacOS and Microsoft Windows systems, with traditional keyboards and mice.	"Dall'Alma Mater al mondo. Dante all'Università di Bologna" 25 October 2021 - 17 December 2021 BUB - Biblioteca Universitaria di Bologna
"*Porcupinefish (Diodon Antennatus)*", wide, highly specular skin and tiny details, Sistema Museale di Ateneo (SMA, Bologna, Italy) of the University of Bologna hosted inside Palazzo Poggi.	350 × 190 × 250 mm (bounding box)	Interactive touch-based visualizer (based on customized RTR Engine: Unity 3D version 2018.4.31)	Touch screen 4K (3840x2160 px), 55 inches, driven by Nvidia Quadro P4000 (8 GB VRAM) GPU. Laptop PC release running on Apple MacOS and Microsoft Windows systems, with traditional keyboards and mice. Mobile tablet MS Surface Go 2, 12.4 inches, driven by Intel UHD Graphics 615 GPU. VR Meta Oculus Go goggles, (2560×1440 resolution, 1280×1440 per eye), 5.5 inches, 60 to 72 Hz refresh rate 12.67 pixels per degree	n/a

Table 2 - Details on the case studies collected to reach a level of iconicity as close as possible to the real artifacts, by self-built tools including custom-developed software and hardware devices..

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Fig. 7 - Perceptually reliable 3D replicas. Leonardo da Vinci, Study of various buildings in perspective (study for the background of the Adoration of the Magi (original drawing on the left, digital RTR replica on the right).

guarantees the necessary perceived fidelity, and it requires an acquisition workflow that was optimized with customized tools [Bacci et al., 2023], following working steps not harmful for the artworks and producing excellent results. From time to time, a tailored interactive RTR environment was developed (adopting software solutions from the videogame entertainment industry) to dynamically showcase these features to various users, enhancing the level of iconicity based on the model's characteristics (such as dimensions, materials used for it, damages or *craquelure*, and responses to light exposure).
Alongside the RTR visual experience, interactions with these models were also refined to allow users to engage with the objects using natural and intuitive gestures, like those commonly used on smartphones or tablets in daily life (Figure 8), avoiding the need for steep learning curves. For example, touch screens were integrated into museum exhibitions showcasing digital replicas, leading to a notable increase in visitor attendance.
Access to nested information or dedicated informational sections, as in the case of the Annunciation, are further facilitated by soft-touch systems with sensitive illuminated buttons, effectively organizing and presenting different topics with clarity: in fact, together with the touch screen, a soft keyboard was built to change the view of the main model and to focus on different portions of the artwork, illustrated by texts popping up on screen when the physical button were touched.
This way the 3D model offers a zoom level impossible to reach with the real painting, covering features explained by experts almost invisible to an unprepared eye (Figure 9).
The adoption of more immersive systems, such as the Oculus headset (in its portable version known as Oculus Go, later evolved in Meta Quest [Meta Quest], was reserved for complex objects, where their understanding may be enhanced by a 360° view accompanied by explanatory texts detailing the model's intricacies, appearing again as pop-ups on a dedicated graphic user interface during the observation through the stereoscopic goggles.

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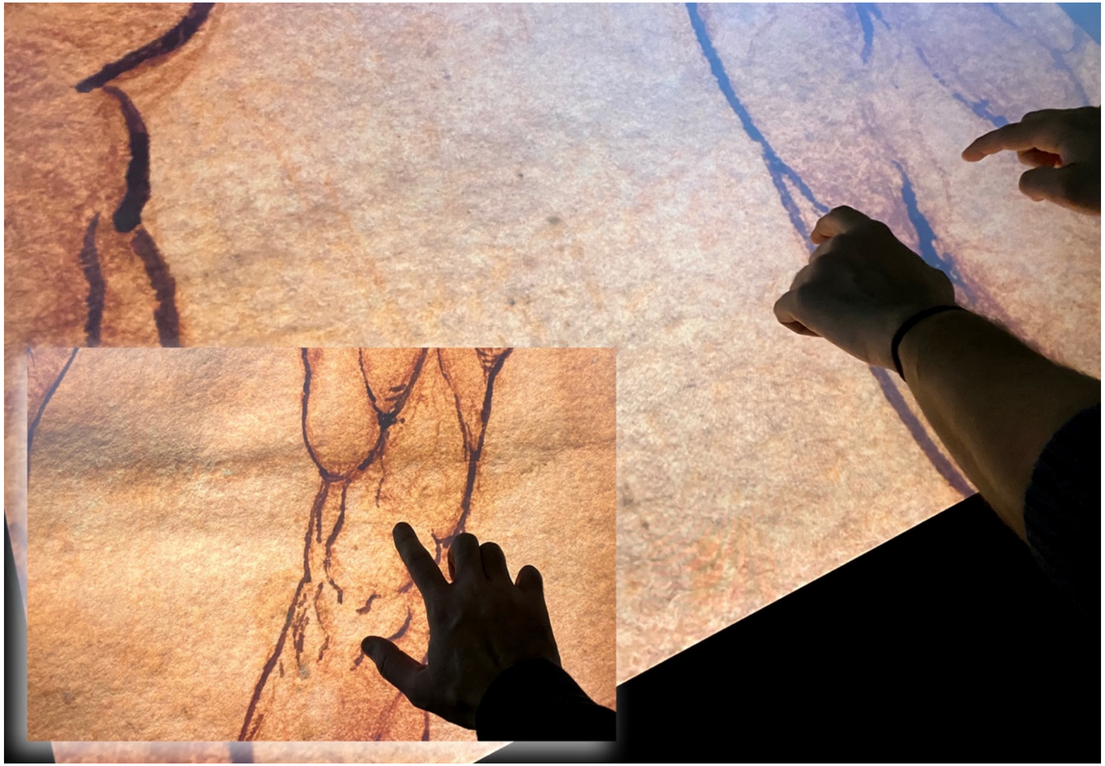

Fig. 8 - Touch interface on a 4K display to explore 3D models using common gestures. Ancient drawings are visible in high resolution, also changing the direction of light sources.

CONCLUSIONS

The outcomes of an iterative refinement of a workflow developed over the years to produce digital replicas of ancient artworks with high levels of iconicity (drawings, manuscripts, paintings, and old artifacts) has been presented in this paper. Beginning from the acquisition campaigns, in which data on these specimens are collected on purpose, the digital replicas may be targeted to many users and ported to many environments to enhance their level of iconicity, according to the different needs expressed by interested actors such as scholars, restorers, and museum visitors. The adaptability to heterogeneous needs reflects a forward-thinking approach to digital replication, while the augmentation of models with alphanumeric data visible when exploring the models enhances their narrative potential, enriching the viewer's experience.

Looking ahead, the field of visualization techniques applied to digital replicas for historic architecture, archaeology, and art museum institutions holds promising perspectives for exploration and innovation: the continued refinement and integration of emerging technologies, such as machine learning and Artificial Intelligence, will likely lead to easier ways to produce replicas once they will be mature enough to enhance the accuracy and realism of digital reconstructions.

Moreover, the wider and wider access to 3D replicas through online platforms and mobile applications has the potential to democratize access to cultural tools, enabling broader audiences to engage with and learn from historical digital replicas regardless of geographical location or physical mobility, uncovering new insights and narratives.

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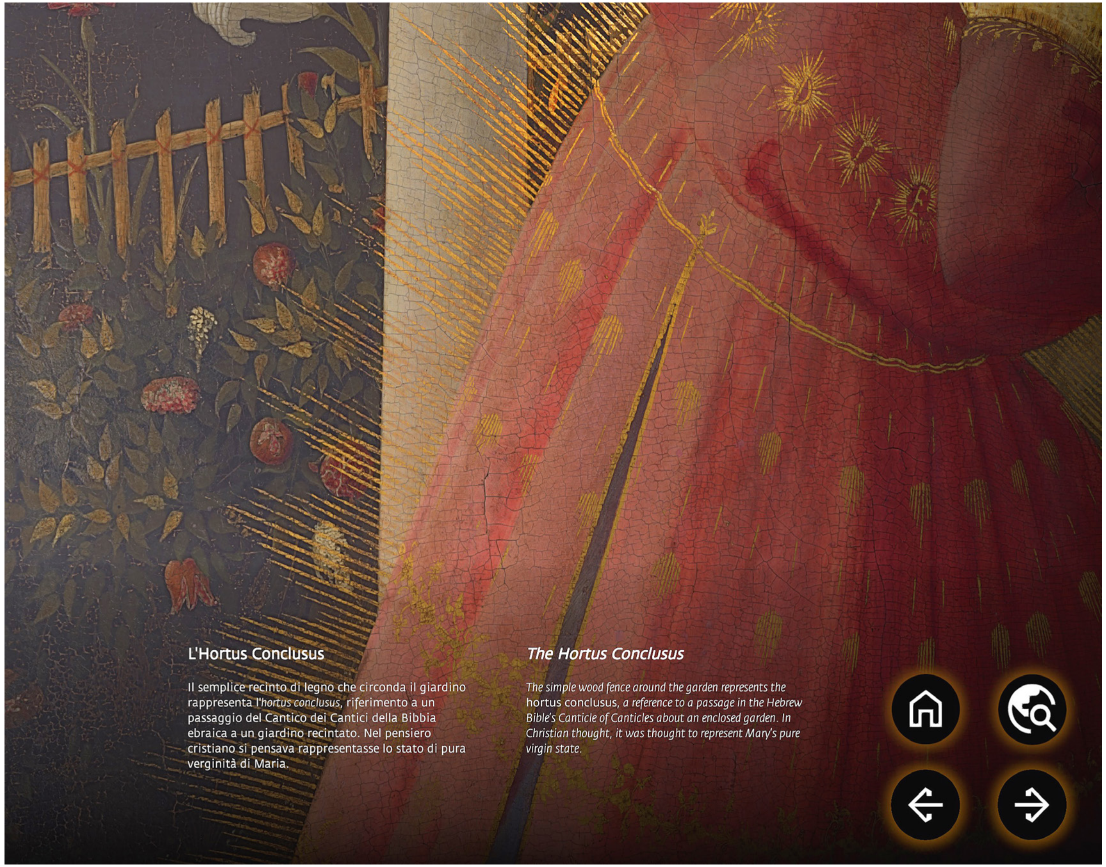

Fig. 9 - The details that can be freely explored in the 3D digital model, with a visualization guided tour augmented by explicative texts, highlights important features necessary to better understand the whole masterpiece (Annunciation, Beato Angelico, detail).

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