

# **The Virtual Reconstruction of a Statue of Isis unearthed at the Roman City of Clunia (Spain): a 3D Model for Interactive Virtual Reality Experiences**

Virtual Reconstruction of Isis Statue from Clunia

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This research aims to contribute to the advancement of technologies applied to the conservation, reconstruction, and dissemination of Cultural Heritage, such as photogrammetry, 3D modeling, Virtual Agents, and Virtual Reality. To this end, the virtual reconstruction process of a Roman alabaster sculpture of the Goddess Isis is presented and assessed in a comprehensive and systematic procedure. Unearthed at the Roman city of Clunia (province of Burgos, Spain), the sculpture dates back to approximately the 2nd c. AD. The virtual reconstruction depicts both existing and missing features, based on the remains and comparisons with other extant representations of the goddess. The generated 3D model was designed to function as a Virtual Agent in interactive experiences. Moreover, discrepancy, detail and vertex concentration analyses of the model yielded satisfactory results. The visualization of the 3D model was tested in an interactive Virtual Reality experience at the Museum of Burgos with 60 participants, whose evaluations were highly positive. Clustering of participant responses revealed behavior patterns that were primarily associated with age and previous experience with Virtual Reality. The 3D model of the virtual reconstruction is open access and free to download.

CCS CONCEPTS •Computing methodologies~Computer graphics~Graphics systems and interfaces~Virtual reality •Computing methodologies~Computer graphics~Shape modeling •Computing methodologies~Computer graphics~Animation •Applied computing~Arts and humanities~Fine arts

**Additional Keywords and Phrases:** 3D modeling, Virtual Reality, Cultural Heritage, Virtual Reconstruction

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## 1 INTRODUCTION

New technologies are increasingly present today and are gaining significant importance within the field of Cultural Heritage (CH) [9], due to their various functions. There are, on the one hand, applications that facilitate the analysis and the conservation of CH [61], assisting work procedures and process documentation [57]. For example, 3D modeling [20], photogrammetry [45], and laser scanning [49] are all now virtually essential in archaeological reconstructions [28]. Such technologies can be used to collect and to process the data needed for virtual reconstructions [75], resulting in a hypothetical 3D view of a CH site or artifact in its original state [31].

On the other hand, there are also new technologies that can serve as tools for the dissemination of CH [47], particularly eXtended Reality (XR) technologies [26], a heading that covers Augmented Reality (AR), Mixed Reality (MR), and Virtual Reality (VR) [10]. Although first used in the CH field in the 1990s [38], their use has gained greater interest within the public domain over the past decade [10]. AR has accompanied the rise of smartphones and the launch of Oculus DK1 has significantly advanced the use of VR [17]. VR has since become widely recognized in its immersive form (iVR), unlike VR, the iVR environment completely envelops a user, perhaps equipped with a Head Mounted Display (HMD) or a Cave Automatic Virtual Environment (CAVE) system [5]. The dissemination of CH through XR technologies, such as iVR, can improve knowledge transmission, especially spatial information [18], by enhancing the clarity of archaeological data and hypothetical visualizations. It can also improve user satisfaction [1], whilst contributing to CH preservation and accessibility [65].

The widespread acceptance of the above-mentioned set of new technologies in the field of CH has seen their introduction alongside traditional musealization experiences [93]. For example, XR has had a significant impact on knowledge transmission [4]. Now integrated in what are known as Virtual Museum (VM) experiences, these digital museum-like experiences also serve to digitize entire collections [92]. VM bridges geographical boundaries and promotes remote access [87]. In this sort of musealization experience, the use of Virtual Humans (VH) or Virtual Agents (VA) is common [84]. Interactive or otherwise, they guide users through the virtual environment [55]. As agents within a virtual environment, they transfer knowledge of intangible heritage and act as virtual guides [55]. In brief, the inclusion of a VH or a VA enhances user satisfaction and assists knowledge transmission [46].

This research aims to contribute to the advancement of technologies applied to the preservation, reconstruction, and dissemination of CH, such as 3D modeling, photogrammetry, and iVR within high-impact contexts such as museums. To this end, the research presents a case study in which these technologies are comprehensively and systematically implemented through the virtual reconstruction and validation process of a Roman sculpture of the goddess Isis, unearthed at the Roman city of Clunia (Spain). For this purpose, a qualitative approach was employed for the historical reconstruction and a mixed qualitative and quantitative approach for assessing the 3D model. The resulting 3D model is designed to function as an open-access downloadable VA ready to use in other iVR experiences. Furthermore, this model has been integrated into an immersive iVR experience, which was validated within a real musealization environment.

The structure of the paper is as follows. In Section 2, related works are analyzed, and the novelty of the study is emphasized. In Section 3, the characteristics of the case study, a Roman statue of Isis, are described. In Section 4, the reconstruction and validation procedure of the 3D model is detailed. In Section 5, an explanation of the development of the iVR experience used to test the 3D model is given. In Section 6, the evaluation process of the iVR experience and its results are detailed. Finally, the conclusions of the study are presented in Section 7.

## 2 RELATED WORK

The virtual reconstruction of statues has been addressed in scientific literature. The state of conservation of a statue determines the process that is followed. On the one hand, if in good condition and intact with no need for further restoration, restoration will typically be focused on its original polychromy. On the other hand, a full or partial reconstruction of a statue in a poorer state of preservation with one or more missing features is usually undertaken.

Various restoration projects have been described in the literature. For example, the restoration of the Lingyan Temple (China) statues, dated between the 11th and the 14th c., whose original polychromy was restored [85], and the sculptures in the Dunhuang Mogao Grottoes (China) where non-rigid transformation was tested for better reproduction of the original textures [96].

Moreover, anastolysis or structural and non-structural reconstruction is necessary when a statue is not well conserved. The anastolysis reconstruction technique involves the reassembly of separate parts to recreate an original piece [21]. One example is the reconstruction of Roman masks found on the island of Lipari (Italy) dating back to the 4th c. B.C., whose reconstruction, after photogrammetry, involved joining their different parts together [56]. However, a reconstruction may also be partially based on anastylosis and combined with other reconstruction techniques, such as the restoration of the statues from the Temple of Zeus at Olympia (Greece) from the 5th c. B.C., for which structural and non-structural reconstruction was used [68]. If anastylosis is not an option, structural and non-structural elements can be reconstructed upon the basis of documentation and comparison with similar artifacts. Examples include the 2nd c. statues of Aesculapius and Hygeia at the Sanctuary of Isis in Lilybaeum (Italy), which were reconstructed using other sculptures as documentation [29], or the circa 1st and 2nd c. AD lion sculptures, respectively, at the Lapidario Estense Museum and at Modena Cathedral (Italy), both also reconstructed using the same method [33]. In some cases, only specific missing components of the sculptures required reconstruction, such as the weapons of the 12th c. Ni-Tennō statues (Japan) [82].

Additionally, some of these reconstructions have been evaluated through XR experiences, such as AR or iVR, to assess the effectiveness of the work in a real dissemination environment. For instance, the reconstructions of the two lions, one at the Lapidario Estense Museum and the other at Modena Cathedral, were tested with an AR application [34], while the reconstructions of the weapons of the Ni-Tennō statues were evaluated through an iVR experience [82].

However, statue reconstructions for the purpose of a VA are relatively uncommon. Typically, a VA (or VH) in a CH experience is used for three main purposes. It first of all serves as an inhabitant of the virtually reconstructed environment [55]. A VA will often serve to convey certain concepts of intangible heritage while also enhancing the realism and immersion of virtual reconstruction. One example is the case of the virtual reconstructions of Mesopotamia circa 5000 B.C. [86] and a pre-Columbian Amazonian village [27], which both used a VA depicted as an indigenous inhabitant of the reconstructed site. Second, a VA can be used to provide instructions or tasks in more complex experiences with challenges. Some examples are the reconstruction of Little Manila in the 20th c. [89] and the Temple of Hera, circa 500 B.C. [67]. Finally, a VA is frequently used as virtual guide to help users understand different parts of the iVR experience, as featured in the reconstructions of the City of Uruk, circa 3000 B.C. [11], the Great Palace of Knossos, circa 1700 B.C. [43] or the iVR experience about the city of Heraklion (Greece) [2] and the iVR experience of the Museo Egizio of Turin (Italy) [12].

Although these studies have significantly contributed to the advancement of this discipline, no research has focused on integrate these outcomes into a systematic and comprehensive process that combines the data acquisition, restoration, optimization, and validation of a statue to produce a 3D model with VA capabilities, ready for use in iVR experiences. In addition, this research evaluates the resulting 3D model through a pilot iVR experience conducted at the Museum of Burgos, involving a highly diverse age group. The outcomes revealed distinct behaviors patterns, identified through a clustering analysis of the participants.

### 3 CASE STUDY: STATUE OF ISIS OF CLUNIA

The sculpture of the Isis of Clunia was unearthed in an area adjacent to the theater, a major archaeological site located at the ancient Roman city of Clunia to the south-east of the province of Burgos (Spain) [8]. Various theories on its original location have situated it among the sculptures around the theater, as shown in Figure 1.1 [59]. The worship of this deity, the mother of Horus, survived assimilation into both the pre-existing Greek and Roman pantheons. As Rome's conquests spread, the gods and goddesses of other cultures were often renamed after existing Roman divinities, although the worship of the goddess Isis continued throughout the Hellenization of Egyptian culture and subsequent Romanization, slowly spreading through Italica into Hispania. The expansion of the cult of Isis during the reign of the Emperor Hadrian has been linked to maritime trading and the status of major cities that would require at least one temple for her adoration [6]. So, the goddess unearthed at Clunia, rather than a typical representation of ancient Egypt, was depicted in the Hellenic style that emerged in Alexandria during the Ptolemaic dynasty of Egypt [94].

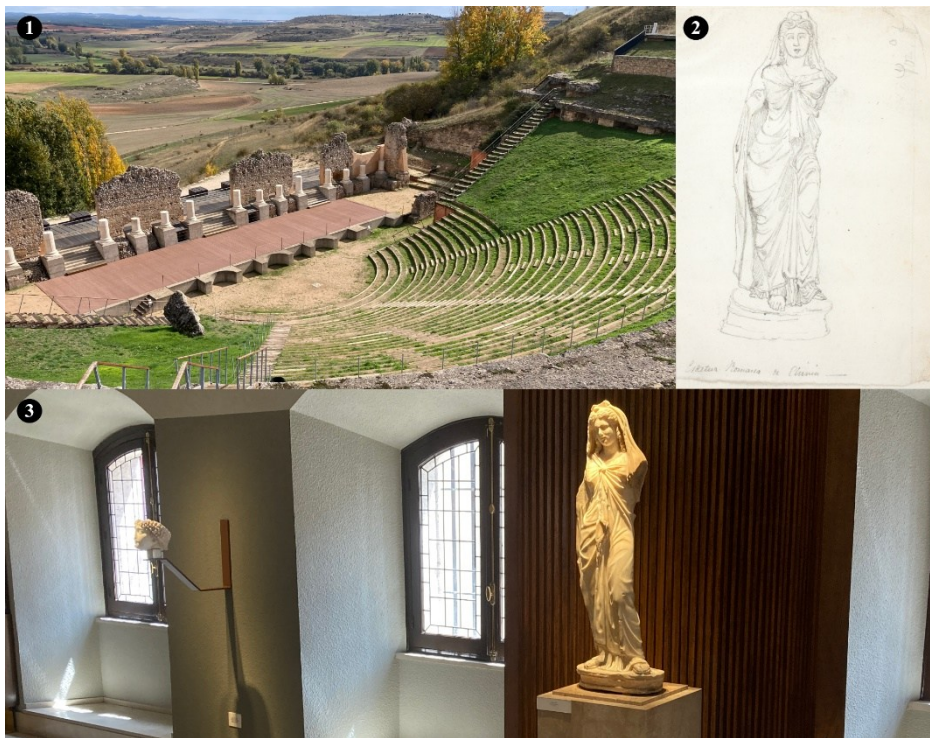


Figure 1: 1) Archaeological site of the theater of Clunia; 2) Cecilio Pizarro “The goddess Isis (Clunia)” compound pencil, 113 mm x 82 mm (D006404/111-04, Madrid, Museo Nacional del Prado, © Archivo Fotográfico Museo Nacional del Prado); and 3) statue of the Isis of Clunia at the Museum of Burgos.

The news of its discovery was documented in an article published by Salomón Remigio in a weekly magazine in 1853 [79], accompanied by a woodcut print of a drawing by Cecilio Pizarro, now conserved at the Museo Nacional del Prado, Madrid (D006404/111-04 [63]), as shown in Figure 1.2. The statue had been found the previous year by Santiago Lucas, in a horizontal and slightly inclined position. A plaque dedicated to the Emperor Hadrian was found nearby: 'To the health of Emperor Caesar, Augustus Hadrian, of the Cluniense Colony' [79], five columns, three small bronze wings, some ceramics, fragments of ivory, and deer antlers [3].

The sculpture of the goddess Isis at Clunia, dated to the 2nd c. AD, rests on a small oval pedestal with a double toroidal profile. Standing at a height of 1020 mm, it was sculpted in a naturalistic style, reflected in an elegant and sensual contrapposto, with the weight of the body resting on the right leg. This creates a sinuous silhouette, with its feminine forms accentuated by the draping of the garments fitted to the chest, abdomen, and thighs. Beneath the tunic, the folds of an undergarment are visible, revealing feet shod in sandals. The shoulder-length headdress defines the oval shape of the face around which curled strands of hair are still visible on either side. One detail that clearly identifies the sculpture as a depiction of the goddess Isis is the presence of the aforementioned Isiac knot [94]. A sign reinterpreted, in the Greco-Roman manner, known for its protective properties [6]. There are also some remnants upon the headdress that could be vestiges of crescent moon [79]. Both arms of the statue are missing, along with the left and the right hand that would in all likelihood have held a situla or ritual pitcher, and a sistrum, an ancient rattle of metal rods, respectively [6]. Figure 1.3 shows the sculpture at the Museum of Burgos (Inv. 27 [70]), its current location.

The analysis of the statue was supplemented by a comparative study of other Roman representations of the same deity, to facilitate the reconstruction process. The missing elements that might further define its iconography could in that way be interpreted on the basis of reliable sources. To do so, sculptures were selected according to their similarity in terms of their state of preservation, arrangement, posture, and other features that might assist with the virtual reconstruction. Among various works, the statue of Isis from the Capitoline Museum in Rome (Inv. Scu 744 [81]), was selected. Although significantly larger than the sculpture unearthed at Clunia, it shares important similarities with its Spanish counterpart. The Capitoline statue (displayed in Figure 2.1) holds a sistrum aloft in its right hand, while the situla hangs loosely below the waistline in the left hand [6]. It should be mentioned that the sculpture has undergone restoration in modern times.

The sculptures from the Museum of Art History in Vienna (Inv. 1-158 [64]), Figure 2.2, and the Museum of Naples (Inv. 6368 [35]), are also of interest, especially as parts of their polychromic coating are still in place. However, the former only showed the handle of the sistrum, the instrument itself having been lost to posterity. Both works and the Capitoline Isis have a headdress partially covering the side of the face crowned with a solar disk, although without the crescent moon diadem upon the Clunia sculpture that is likewise no longer with us. It was therefore logical to search for such distinctive symbols on other statues. One example was found at the National Roman Museum of the Baths of Diocletian [36] in Rome, shown in Figure 2.3. Here, the lunar horns support the solar disk, although without a headdress. In that way, examples of all the distinctive iconographic symbols no longer part of the sculpture under reconstruction could be assessed.



Figure 2: Isis statues: 1) Capitoline Museum, Rome (Image by © Sailko, licensed under CC BY 3.0, available on Wikimedia Commons [78]); 2) the Museum of Art History, Vienna (Image by © Gryffindor, licensed under CC BY 2.5, available on Wikimedia Commons [37]); and 3) National Roman Museum of the Baths of Diocletian, Rome (Image by © Carole Raddato, licensed under CC BY-SA 2.0, available on Pinterest [13]).

#### 4 3D MODEL DEVELOPMENT AND ASSESSMENT

The reconstruction process is summarized in Figure 3, in the same order as Sub-section 4.1. Reconstruction procedure. The purpose of this procedure is to achieve a faithful reconstruction of the historical-archaeological documentation described in the previous section, to obtain a realistic 3D model that could be used as a “game-ready” asset in a game engine. Due to this and considering that the reconstruction process significantly alters the appearance of the piece, this procedure has prioritized optimization over the preservation of a ground-truth surface. Subsequently, the validation procedure applied to the resulting 3D model will be detailed in Sub-section 4.2, Model Assessment. The 3D model in .fbx format can be consulted and downloaded in Annex I.

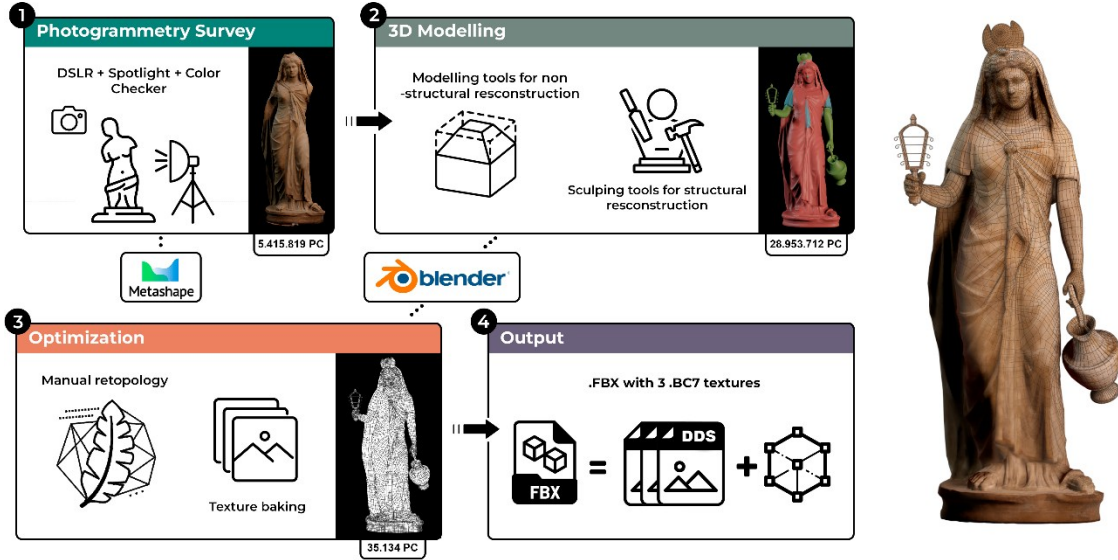


Figure 3: Summary of the reconstruction procedure.

#### 4.1 Reconstruction procedure

A photogrammetric survey was the first step of the reconstruction procedure. In this case, the photogrammetric survey of the statue served as the basis for the subsequent introduction of all the secondary documentation described in the preceding section [40]. A procedural phase that is summarized in Figure 3.1.

A conventional low-cost set of instruments was used for close-range photogrammetry, as described in several works [42, 52]. The instruments were a Fujifilm X-T20 Mirrorless DSLR camera equipped with an APS-C sensor of 24 megapixels. Additionally, two diffuse light sources were employed to compensate for the ambient lighting conditions of the museum, as shown in Figure 1.3. A Calibrate Color Checker Passport Photo 2 was also used to perform white balance calibration and ensure accurate color capture. This calibration target includes a reference square of 50 mm, which was used as a scale reference for the photogrammetric model. Image capture was configured with a focal length of 33 mm (equivalent to 50 mm on a full-frame sensor), ISO 640, an aperture of F/6.4, and a shutter speed of 1/30 s. These capture parameters remained consistent throughout the acquisition process, which is a key factor for the successful development of the image data acquisition phase [80]. The chosen specifications aimed to maximize image homogeneity and minimize noise, taking into account the museum's lighting conditions. A total of 193 images were captured in RAW format at a resolution of 6000×4000 pixels. The quantity and resolution of the images are comparable to those used in other datasets for image-based 3D reconstruction [48], providing a high degree of overlap between frames, an essential factor for the successful generation of the photogrammetric model [72].

Photogrammetry was selected as the acquisition method for several reasons. First, it is the most widely used and accessible technique, which not only aligns with the team's prior experience but also enhances the replicability of the workflow in future studies [73]. Second, while other acquisition methods may offer higher geometric accuracy, photogrammetry excels in capturing high-quality color and texture information, making it one of the most popular techniques in archaeological documentation [51]. Moreover, in subsequent stages of the procedure, texture quality will be prioritized over surface fidelity to optimize the model, as it represents one of the most critical aspects in the optimization of 3D models, since much of the simplification of the 3D model occurs at the surface level [23]. Consequently, the

deviations introduced by photogrammetry, are potentially in the range of a few millimeters under suboptimal conditions [73].

For image processing, Agisoft Metashape was selected, with which the research team was familiar and that is widely used in photogrammetry projects [45]. Upon completion of this phase, the 3D model contained a Polygon Count (PC) of 5,415,819 triangles. Handling such a dense mesh in the subsequent stages of the workflow may be computationally demanding, particularly for devices with limited hardware resources. An alternative approach would be to generate a lighter, optimized mesh directly within the photogrammetry software. However, this would result in a less accurate model.

Subsequently, the historical-archeological information detailed in Section 3 was incorporated into the photogrammetric model to complete the missing parts of the sculpture. A summary of that phase in the procedure is shown in Figure 3.2. To do so, two different methods were followed. Firstly, digital sculpting was used to reconstruct elements requiring structural restoration, such as the statue's nose. The choice of that technique was because it enables easy modification of such elements as the body of the sculpture. Secondly, 3D modeling was employed to reconstruct parts that needed non-structural restoration, such as the situla and sistrum, held in the left and the right hand of the reconstructed statue, respectively. The 3D models generated in this phase were created entirely from scratch. This procedure was selected rather than using photogrammetric models as a base, for the following reasons. Firstly, due to the geographical and administrative challenges involved in capturing photogrammetric data of the other statues located in different museums. Secondly, the varying sizes and poses of the other sculptures would have required adaptations regardless, limiting their usefulness as direct references. Likewise, their development was based on the historical-archeological information presented in Section 3, and the process underwent several rounds of review by history of art experts. The 3D modeling was utilized because it is often used to create geometric models from scratch.

Then, using the digital sculpting tool, some of the reconstructed parts, such as the arms and the crown, were merged with the photogrammetric model. Following a working principle of restoration that restored parts should be visibly distinguishable, a slightly different material was used for the reconstructed parts. This material was created by cloning the preserved parts of the sculpture. The entire phase was carried out using Blender 3D modeling software, version 3.6 Long Term Support (LTS). Blender was chosen, as it is an open-source software, making it one of the most popular CH research software packages [47]. Additionally, the research group has gained experience with that software in other CH modeling projects [18]. Other widely used software solutions for these purposes include Cinema 4D, 3D Studio Max, and Maya; however, their high cost represents a significant limitation for many research and development contexts [76]. Upon completion of that phase, the 3D model contained a total of 28,953,712 triangles. The use of the digital sculpting tools with the photogrammetry-based model explains the higher PC, as it was configured to modify the topology of the 3D model by generating additional polygons. Topology alteration is a recommended process to preserve the surface of the photogrammetric model, since not generating new polygons would require repositioning the existing ones, thus modifying the shape of the piece. However, this drastic increase in PC can lead to performance issues on low- and mid-range computer systems.

The results of both phases of the procedure are illustrated in Figure 4. Firstly, the photogrammetric 3D model is shown (Figure 4.1), followed by the completed reconstruction (Figure 4.2), and finally, the Extended Matrix archaeological evidence scale (Figure 4.3). Extended Matrix and its toolkit are designed for virtual heritage reconstruction and transparency [21]. In this project, the various sources used in the reconstruction were checked against the Extended Matrix properties scale. The properties of an artifact are classified in eExtended Matrix, although all levels of evidence not used in this reconstruction were omitted, is shown to the left of Figure 4.3. The color coding of the scale refers to: 1) the extant parts (generated through close-range photogrammetry) in red; 2) the structural reconstructions (generated through digital

sculpting) in blue; and 3) the non-structural reconstructions, based on the documentation detailed in Section 3 (generated through 3D modeling) in green. The visualization of such data is of great importance in the CH domain, as transparency is one of the fundamental principles of the London Charter [22].



Fig. 4: Reconstruction phases: 1) photogrammetric model; 2) reconstructed model; 3) scale of archaeological evidence.

Finally, the reconstructed model was optimized, so that it was ‘game-ready’, and its functions could be seamlessly incorporated into a game engine. It involved a common optimization process for using a model in game engines [83], by reducing both the number of vertices and the number of textures and materials used in the model, as 3D model generation processes based on photogrammetry typically result in a very high number of triangles [30]. This process is crucial for the proper functioning of 3D models in interactive environments, but particularly in iVR, due to the more limited resources available on these devices [16]. In addition, in this project the optimization process ensured that the model could be used as a VA. This process necessarily involves a simplification of the 3D model’s surface, although its visual appearance will be preserved. For this reason, it is preferable to use a data acquisition method that excels at preserving textures, as these will not be simplified during the optimization process. Moreover, textures play a key role in visually conveying part of the geometric detail lost during simplification [23]. This process, therefore, constitutes a trade-off between surface fidelity and ensuring usability in interactive environments [71]. This phase of the procedure is summarized in Figure 3.3.

First, the number of the 3D model vertices was reduced through retopology, a process that remodels an existing 3D model with a mesh that has fewer polygons than the original model [60]. Typically, the process is performed in the CH domain using automatic retopology tools, such as those available in Z-Brush or Blender [25]. Their results are satisfactory, but a sufficient level of adequacy for more complex contexts, such as animation, is not achieved [14]. In this work, a manual retopology procedure using the Blender modeling toolkit was carried out, in a process through which all the polygons of the new (Low-Poly) model were manually generated and connected, while maintaining the shape of the reference (High-Poly) model. Manual retopology permits a drastic reduction in the number of triangles (5,415,819 vs 35,134), thereby enabling a mesh of polygon loops to recreate the 3D shape in future animations.

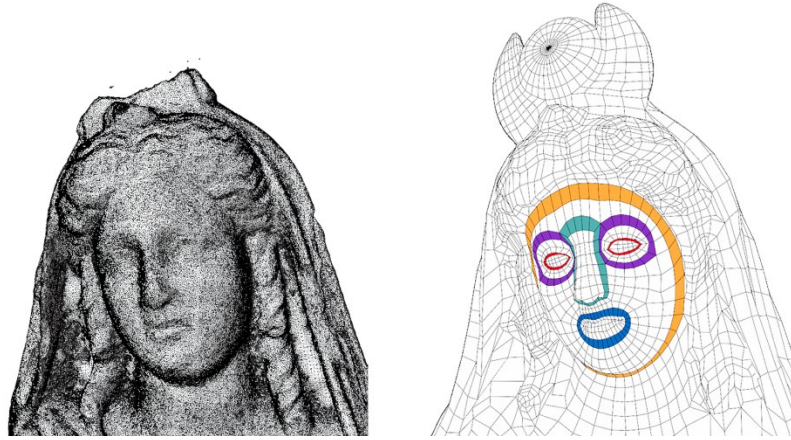


Figure 5: Face mesh from the photogrammetry model (left); face mesh of the retopologized model with some of its edge loops marked in color (right).

An edge loop is a continuous line of polygon edges that loops around a mesh to connect with itself, forming a complete loop. The placement of edge loops is a very important factor in model deformation and the loops play a fundamental role in 3D model animations, which rely on mesh deformation to generate new shapes [20]. The flow and the loops of the Low-Poly model were designed to follow the anatomical shapes of the sculpture, so that the mesh deformations seemed to be as natural as could be. Additionally, the polygon flow was aligned, in so far as possible, with the wet drapery effect of the clothing on the asymmetrical posture of the statue, while ensuring connectivity with the other loops. Finally, a higher density of polygons was concentrated in areas with multiple joints (i.e., the hands) to reflect movements of greater complexity. An example of the use of edge loops on the face of the sculpture is shown in Figure 5 where the photogrammetric mesh is shown on the left, and the retopologized mesh, on the right. The left-hand side of the figure shows some of the most important loops, such as the eyes, the nose, the mouth, and the face, which are traced out with colored lines. Movements reflecting contraction and expansion of, for example, facial features can be achieved with the polygon structure in those areas, lending greater expressiveness to the 3D model. This aspect is particularly important when creating models intended for animation, as in the case of a VA. For a non-interactive model, automatic retopology could be used, which would simplify the process. However, this approach requires significant prior experience in 3D modeling to be carried out effectively. Upon completion of that phase, the 3D model was composed of 35,134 triangles.

Finally, all the details from the High-Poly model were transferred to the Low-Poly model through baking and texture reprojection. Both techniques are widely used procedures in projects with similar retopology workflows [66]. In that way, geometric details of a 3D model may be transferred to a texture, resulting in significant PC savings [15]. To do so, a cage model that enveloped both the High and the Low-Poly models was created, serving as a spatial reference for texture reprojection. The cage must encompass both models and as accurately as possible resemble their shapes for the process to function properly. In this study, the cage properly enveloped both models after modifying the Low-Poly model. The entire Low-Poly model was unwrapped to reduce the number of textures and so that it occupied the full UV space. Additionally, Physically Based Rendering (PBR), which combines various textures that simulate the physical properties of an object [23], was used to create material textures with realistic reactions to any type of lighting. It is a key feature for enabling a 3D model to be incorporated into a wide variety of photorealistic environments.

A total of 3 textures were created with the standard PBR methodology:

1. Diffuse texture: a Red, Green and Blue (RGB) texture that encodes information on model colors, disregarding specular reflection [95]. The final texture was generated by reprojecting the diffuse texture of the High-Poly model onto the UV space of the Low-Poly model.
2. Normal texture: an RGB texture that encodes the direction of surface normal vectors using the RGB channels for each axis [69], so that non-existent geometry may be simulated. The normal texture was generated by baking the geometry of the High-Poly model.
3. Roughness texture: a Black and White (BW) texture that contains information on the degree of dispersion that light should adopt when in contact with the object [24]. The texture was generated with the Blender rendering engine that calculates material roughness.

A metallic texture can also be created to distinguish metallic properties [44], though it was unnecessary in this reconstruction with no metallic parts. The entire process was completed with the Blender modeling toolkit. This process could also be carried out using software such as Adobe Substance, although it is a proprietary option [29]. All 3 textures and their effects on the 3D model are shown with a white material in Figure 6. The textures were compressed with the BC7 codeq in .dds, a format that minimizes compression losses and that is easy to decompress, so that it is especially suitable for real-time rendering. Although there are other formats or codecs that can reduce file sizes even further, the BC7 real-time decompression time is at present one of the shortest. The reconstruction procedure therefore produced a 3D model, consisting of 35,134 triangles, and a material composed of three 4k textures with low compression rates. For its distribution, the .fbx format was chosen, although other popular options such as .obj. Currently, .fbx is the standard for the integration of 3D models into development engines. In addition, .fbx allows for seamless integration other metadata, such as animations and textures [32], which is of great importance in a textured 3D model that can also be used as a VA.

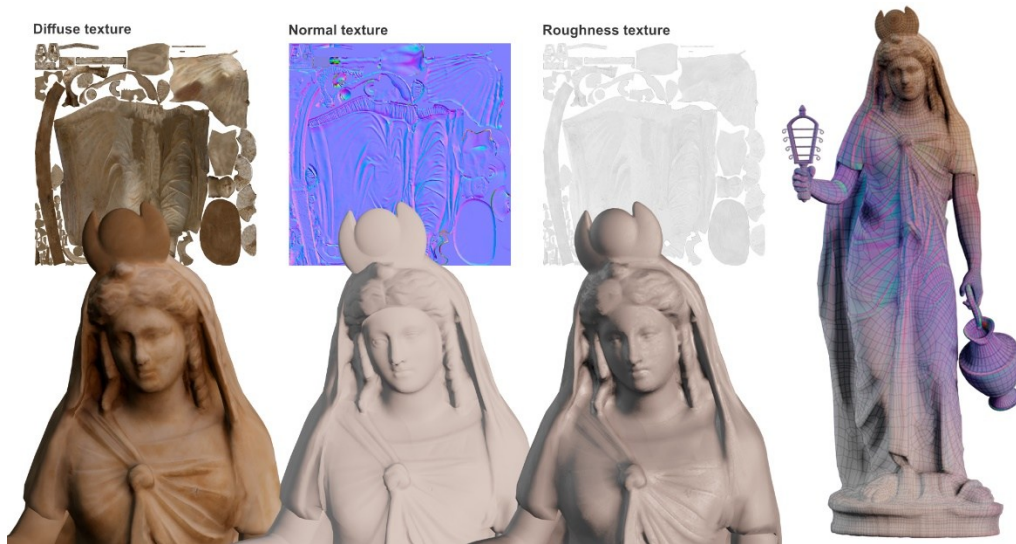


Figure 6: Images of the 3 textures and their effects on the 3D model: diffuse texture (left); normal texture (center); and roughness texture (right).

## 4.2 Model assessment

Finally, three analyses were conducted to assess the technical specifications of the model and the procedure: a discrepancy analysis of the reconstructed 3D model (Low-Poly) compared to the photogrammetric model (High-Poly), a detail concentration analysis and a Level of Detail (LoD) analysis. The analyses were carried out with respect to the photogrammetric model. The purpose of the analyses was to verify correct execution of the retopology process that should maintain the shape of the photogrammetry and place the highest number of vertices in the most relevant and expressive areas of the 3D model with a suitable LoD. Since the optimization process involves a trade-off between surface fidelity and compatibility with interactive environments, it is crucial to ensure that this process has been carried out correctly. Otherwise, part of the surface fidelity may have been lost, something of great importance in CH work [22], without achieving any actual improvement to the 3D model.

The discrepancy analysis was conducted using the software Cloud Compare, a standard open-source tool [53]. The reconstructed parts that could not be compared were excluded from the analysis, since there was no photogrammetric reference. The minimum and the maximum distances between both models were -39.65 mm and 26.63 mm, respectively, with a Mean (M) of 0.4 mm and a Standard Deviation (SD) of 3.7 mm. Figure 7 displays the heatmap generated from the analysis. Both the lower and the upper thresholds were adjusted from -15 mm to 15 mm, so that the deviations of the model could be seen more clearly. Accordingly, blue represents negative and red represents positive deviations. An enlargement of the upper torso of Isis showing the most pronounced deviations can be seen below in Figure 7.

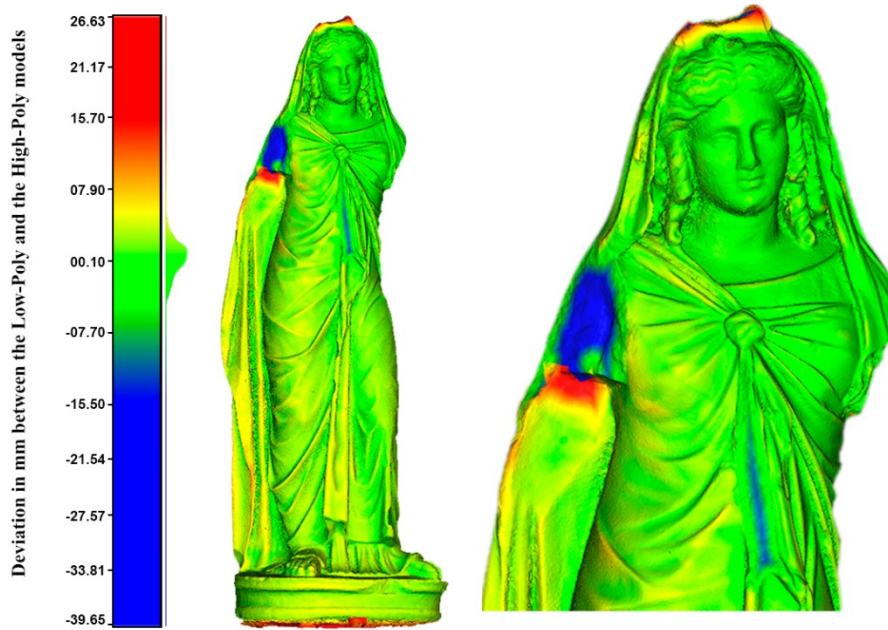


Figure 7: Results of discrepancy analysis heatmap with enlargement of the upper torso (right).

The results indicated that, on average, the deviation of the model was around 1 mm with a SD of 4 mm. Such a relatively high SD was very likely due to localized maximum deviations, which reached up to 40 mm. Significant deviations that may be attributed to the restored parts of the model, shown in Figure 7, where the lower part of the knot of Isis is highlighted

in blue. The heatmap of the model, shown in Figure 7, represented most of it in green, indicating deviations of at most  $\pm 1$  mm. Additionally, all deviations were either concentrated in the reconstructed parts (crown and lower part of the knot) or near the shoulders, which connected to the newly reconstructed parts. These areas were excluded from the Low-Poly model to enable a more accurate analysis; however, the lack of nearby geometric references eventually led to the appearance of deviations in the results. This occurred because the optimization process was carried out using the fully reconstructed statue, not just the photogrammetric model. The only exception was on the left-hand side of the mantle, due to its more complex shape. It would require further geometry for a completely accurate representation. The analysis demonstrated satisfactory overall results, generally showing deviations around 1 mm in a full-size 1020 mm high model.

For the analysis of detail concentration assessment, both a qualitative and a quantitative analysis were conducted. For the qualitative analysis, the MeasureIt add-on, with which metric measurements can be taken within the Blender environment and other Blender add-ons were used. The latter software was chosen out of convenience, as it is pre-installed with Blender. Various areas were calculated, and the number of their vertices were counted. The segmentation of the statue into its constituent parts was based on semantic and anatomical criteria. The results of the vertex count, area, and average vertex density per  $\text{cm}^2$  are shown below, in Figure 8, for each part of the model. The vertex concentration of the model is also shown in the same Figure using a color-coded heatmap in blue and red where darker tones of red indicate higher concentrations.

These data reveal that the lowest detail concentration is found in the mantle, tunic, arms, and pedestal. Conversely, the highest detail concentration is observable in the head, hands, feet, knot and instrument. Throughout the model development process, efforts were made to prioritize retopology, by enhancing detail in elements of significant iconographic importance or areas with high expressiveness, essential for accurate animation. In that regard, the most important iconic symbols of the goddess, her situla, the sistrum and the Isaic knot, the hair, and her headdress were modeled in detail. Although the tunic and mantle had the lowest vertex concentrations, they were detailed for an accurate depiction of the wet drapery effect, as shown in the vertex distribution in Figure 8. In contrast, the face and hands, as expressive features that were crucial to the animation, were highly detailed [14]. Facial details, critical for facial expressions, were specifically concentrated around the mouth, nose, and eyes. The high vertex concentration at the sculpture's feet was because the vertices were at the endpoints of many loops within the 3D model.

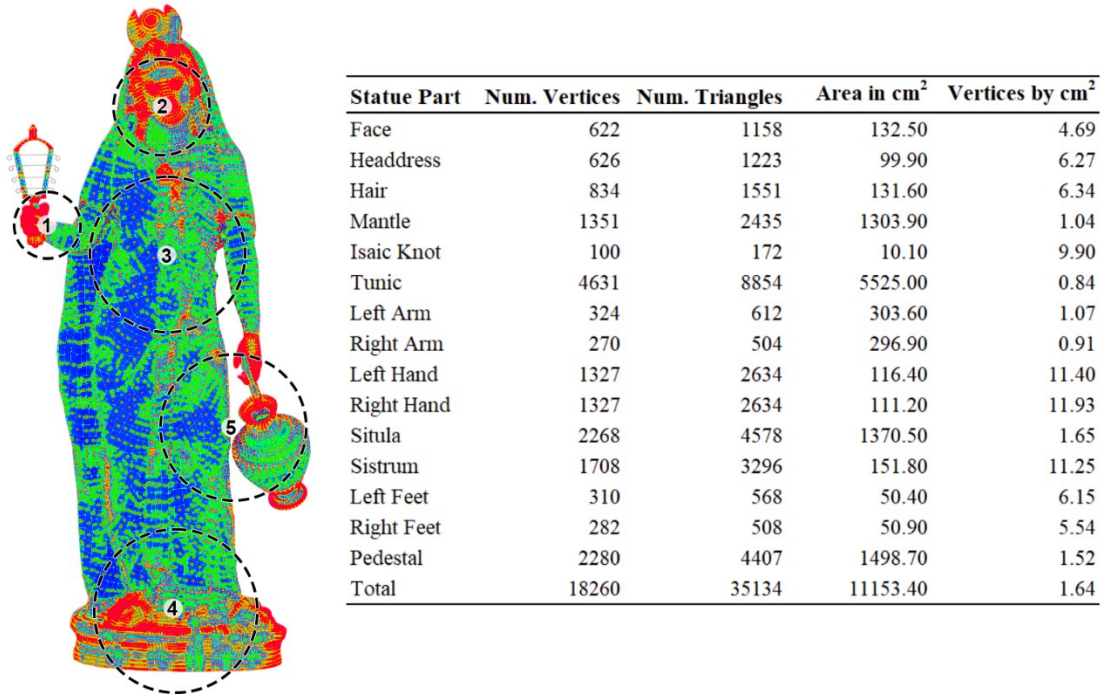


Figure 8: Results of the detail concentration analysis. Heatmap (left) and table results (right). The clusters within the 3D model, defined based on vertex concentration, are represented over the heatmap. Each cluster is labeled with its corresponding centroid number, and the cluster radius is indicated by a black dashed line.

For the quantitative analysis, a clustering of regions within the 3D model was performed using the k-means algorithm. To conduct this analysis, the Euclidian coordinates of each vertex were extracted and subsequently subjected to the clustering process. The entire procedure was carried out using the Hartigan-Wong algorithm, with a varimax rotation of 10 [39]. Initially, clustering was performed using a range of 1 to 10 clusters. The Elbow Method was then applied to evaluate the Within-Cluster Sum of Squares, revealing that the most significant drop occurred at five clusters. Beyond this point, the improvement from adding more clusters became marginal, indicating that 5 is the optimal number of clusters. Subsequently, spheres were modeled around each cluster using their centroids as centers in order to determine the spatial area occupied by the clusters within the 3D model. The standard deviation of each cluster was calculated to define a representative radius, indicating its spatial extent in the 3D environment. Specifically, the square root of the Within-Cluster Sum of Squares was divided by the number of points in the cluster. The resulting value reflects the average dispersion of points around each cluster centroid. Figure 8 shows the identified clusters, outlined with dashed black lines over the 3D model's heat map. Each cluster is labeled with its corresponding centroid number. All relevant data regarding the clusters and their generation are provided in Annex II. As illustrated in Figure 8, the results of the quantitative analysis support the findings of the qualitative assessment. The areas highlighted by the clusters correspond to the hands and instruments, head, feet, and the central region of the model near the knot. These regions are also the most visually prominent on the heat map. Moreover, the segmentation of the model based on semantic criteria, also visible in Figure 8, shows that these areas contain

the highest concentration of vertices. This confirms that these regions of the 3D model are the most relevant in terms of detail, as well as the most expressive areas, where the key attributes of the deity are also located.

For the LoD analysis, LoDCalculator, an add-on for Blender designed to evaluate LoD, particularly in 3D models of CH [76] was used. This software provides a score of 1 out of 5, with half-point increments. The model received a score of 4 out of 5, indicating a high LoD. However, this score is primarily due to the "low" resolution of textures applied to the goddess's instruments. Since these objects did not have a primary reference based on photogrammetry [62], priority was given to displaying the rest of the sculpture to occupy a larger area in the UV space, resulting in a relatively lower resolution for the instruments [34]. Excluding the instruments from the analysis, the LoD score reaches 5 out of 5. Nevertheless, a score of 4 out of 5 still indicates a high LoD [76]. These results are indicative, but in any case, they suggest that the generated 3D model has a high LoD.

## 5 DEVELOPMENT OF IVR EXPERIENCE

An iVR experience was designed to test the 3D model. Created in collaboration with the Museum of Burgos (Spain), it was tested with the museum's visitors during an annual 'White Night' cultural event, during which the city museums remain open during the event and receive large numbers of visitors.

The aim was to test the quality of the model in an iVR experience, so it was necessary to create a 6 Degrees of Freedom (6DoF) iVR experience, so that users could freely look at and move around the virtual environment [77]. The experience followed a simple design process, due to the limitations of the evaluation context. As noted in various reviews, iVR experiences within museums are often more limited than in other contexts, because they are usually tested with very large and diverse groups [10]. The large number of people testing the experience, and the diversity of profiles complicate the execution of complex experiences and evaluations, as situational control is reduced [75]. This aspect has been particularly important in this experience, as the 'White Night' is an event that attracts a particularly large number of visitors. In other contexts, less constrained experiences could be considered.

The iVR experience was of the Explorative type, meaning that users could not directly interact with the environment and their range of movement was limited [17]. A Real Walink-type interaction system [7], also referred to as Room Scale in other reviews [75], was used in which the user can only interact within the environment by walking around it. The movement area of the experience is approximately 2m<sup>2</sup>. Rather than other more complex systems, its use removes the need to include controllers or hand-tracking systems and simplifies the iVR experience, making it more accessible to all kinds of participants. In this iVR experience, users can view the photogrammetric sculpture of Isis and its reconstructed version for a total of 2 minutes (1 minute per version); information that is communicated to the users through a visual message before the experience begins. The user appears in front of the photogrammetry sculpture, displayed at real size, and can move around it for close examination. Due to the high PC of the photogrammetric version of the model (5,415,819 triangles), a decimated version with a PC of 24,406 triangles was generated. One minute later, the photogrammetric version of Isis is replaced by the reconstructed version of Isis. So that the change is clearer for the user, the virtual environment also changes: while the users are observing the photogrammetric version, they are in a museum; when they see the reconstructed version, they find themselves within a Roman temple dedicated to the goddess. No specific heritage site is reconstructed in the temple environment. These genetic scenarios were obtained from the Unreal Engine Marketplace, now known as Fab. Figure 9 shows an image of the iVR experience depicting both scenarios and reconstructions of Isis. A background ambient soundtrack remains on throughout the experience.

The experience was developed for standalone HMDs (Oculus Meta Quest 2 and 3) using Unreal Engine 5. It was the chosen type of HMD, because it requires no computer to function [5], facilitating both its transport and installation in a

museum. Additionally, Unreal Engine was selected for its capability to generate photorealistic environments [10], due to the research team's prior experience with this engine and its ease of use [57].

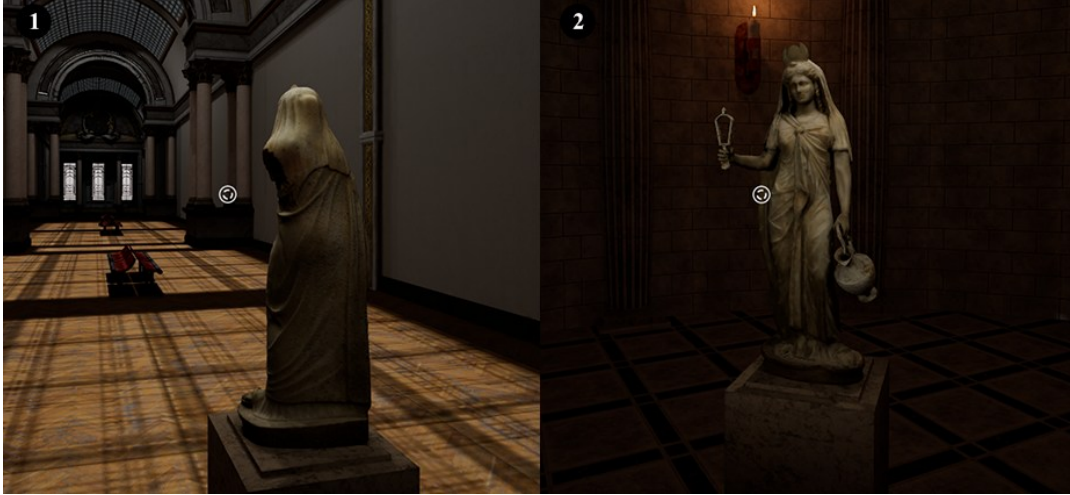


Figure 9: Screenshots of the iVR experience: 1) the original Isis and 2) the reconstructed Isis.

## 6 EVALUATION

The main characteristics of the evaluation will first be described, followed by the results and discussion.

### 6.1 Materials and Methods

The evaluation procedure consisted of a single questionnaire administered at the end of the experience. Although administering questionnaires both before and after the iVR experience can be useful to obtain more robust results [75], only one questionnaire was administered to simplify the evaluation method. A more complex evaluation method with multiple tests could in a context of limited control over the users have led to errors [88].

The questionnaire was derived from the Questionnaire sur l'État de Présence [91], a 2005 revision of the Presence Questionnaire (PQ) proposed by Witmer B.G. and Singer M.J. [90]. The aforementioned questionnaire was chosen, as it is recognized as a standard for the evaluation of various factors related to iVR experiences [50].

The PQ was slightly modified to meet the specific needs of the experience. Firstly, its original 7-point Likert scale was adjusted to a 5-point scale for the purpose of simplification. A change that was due to the challenges of conducting an evaluation in a musealization context. Secondly, due to the limitations of the experience in terms of complexity, all questions directly related to interaction or controls were removed, including all questions on the Interface Quality factor, which refer to the quality of the interface and control [90]. Finally, two new blocks of questions were added. The first block contained demographic questions such as age, gender, and previous experiences with iVR. The second block consisted of questions specific to the experience, focusing on the realism of the 3D model and the quality of the reconstruction; regarding these questions, participants were informed that the environments in which the statue was placed were generic, and that the questions specifically referred to the figure of the goddess Isis. In addition, a question about

cyber sickness symptoms, a very important factor for the assessment of iVR experiences, was also added [7]. Table 1 lists the questions. Considering the above adjustments, the factors evaluated in the final questionnaire were as follows:

1. Cybersickness: a condition marked by symptoms such as nausea, and headaches experienced by users in virtual reality (VR) environments, which have primarily been explained through sensory conflict theory [19]. The cybersickness factor was evaluated with 1 question.
2. Involvement: a psychological state that arises from directing mental energy and attention toward a coherent set of stimuli or activities. It is enhanced by tasks and activities that cognitively, physically, and emotionally stimulate, challenge, and engage an individual [91]. The involvement factor was evaluated through 9 questions.
3. Adaption/Immersion: terms used to describe the degree of the user's perceived competence at navigating the virtual environment and how quickly they can adjust to the iVR experience [90]. The adaption/immersion factor was evaluated with 5 questions.
4. Visual Fidelity: used to evaluate the ease of viewing using vision throughout the iVR experience when conducting active searching, surveying, or examining objects [90]. The visual fidelity factor was evaluated with 2 questions.
5. Reconstruction questions: used to evaluate specific aspects of the restoration work in this project. The reconstruction evaluation factor was evaluated with 3 questions.

Table 1: List of questions used in the questionnaire

| N  | Factor                   | Item                                                                                                                   |
|----|--------------------------|------------------------------------------------------------------------------------------------------------------------|
| 1  | Demographic              | Sex                                                                                                                    |
| 2  | Demographic              | Age                                                                                                                    |
| 3  | Demographic              | Have you ever used a Virtual Reality headset before?                                                                   |
| 4  | Cybersickness            | Did you feel dizzy during the experience?                                                                              |
| 5  | Involvement              | How much were you able to control events?                                                                              |
| 6  | Involvement              | How responsive was the environment to actions that you initiated?                                                      |
| 7  | Involvement              | How natural did your interactions with the environment appear?                                                         |
| 8  | Involvement              | How much did the visual aspects of the environment involve you?                                                        |
| 9  | Involvement              | How natural was the mechanism which controlled your movement through the environment?                                  |
| 10 | Involvement              | How compelling was your sense of objects moving through space?                                                         |
| 11 | Involvement              | How much did your experiences within the virtual environment appear to be consistent with your real-world experiences? |
| 12 | Involvement              | How involved were you in the virtual environment experience?                                                           |
| 13 | Adaptation/Immersion     | Were you able to anticipate what would happen next in response to the actions that you performed?                      |
| 14 | Adaptation/Immersion     | How completely were you able to actively survey or search the environment using vision?                                |
| 15 | Adaptation/Immersion     | How much delay did you experience between your actions and the expected outcomes?                                      |
| 16 | Adaptation/Immersion     | How quickly did you adjust to the virtual environment experience?                                                      |
| 17 | Adaptation/Immersion     | How proficient in moving and interacting with the virtual environment did you feel at the end of the experience        |
| 18 | Visual Fidelity          | How well could you examine objects from multiple viewpoints?                                                           |
| 19 | Visual Fidelity          | How closely were you able to examine objects?                                                                          |
| 20 | Reconstruction questions | How realistic did you find the sculpture of Isis?                                                                      |
| 21 | Reconstruction questions | Do you think the 3D model you have seen faithfully reproduces the appearance of Isis?                                  |
| 22 | Reconstruction questions | Were you able to differentiate the reconstructed parts from the original parts of the sculpture?                       |

## 6.2 Results and discussion

Firstly, the demographic results are detailed. Secondly, the results of the factors that were analyzed are explained and discussed. Finally, the results of a clustering analysis on user behavior are presented.

The 60 individuals of the evaluation sample had a mean age of 47 years old with an SD of 17 years. There were 33 (55%) women and 27 (45%) men, 43% of whom had previous experience with iVR. Figure 10 shows a group of users viewing the experience during the ‘White Night’ event. The data were processed by calculating M and SD. The results of Question 15 were reversed, with maximum and minimum values inverted, as it was the only question posed in reverse order. All the data can be consulted in Annex 2. Table 2 presents the sample results for each factor, showing M and SD. Considering that the musealization experience is designed for a diverse range of users, the results were categorized based on the demographic profiles of the users, to assess their impact on each factor. The results were divided into groups based on their prior iVR experience and age, splitting the sample into four equal quartiles of 15 individuals with the following characteristics: Age Group 1 (10-34 years old), Age Group 2 (34-53 years old), Age Group 3 (54-60 years old), and Age Group 4 (60-75 years old). In that way, age-related differences could be identified in view of the wide age range of the sample.



Figure 10: Group of users testing the experience during ‘White Night’ event.

Overall, the results of the study were highly satisfactory, with Visual Fidelity, at 3.73, being the only factor scoring below 4 out of 5. There were minimal differences between the other groups, with Age Group 3 standing out for having a slightly higher score, except in Cybersickness. These results can be contrasted with the results of other studies, in which iVR experiences were evaluated in museum contexts with large samples and wide age ranges. The way that the results were affected by age, due to factors such as the younger populations' experience with new technologies [67], interest in new technologies [54], and perception of CH [74] can be highlighted in this research. In addition, these results could also have been affected by the novelty effect, i.e, the excitement that any new technology causes in new users, enhancing their

attention during initial interactions [58]. An effect that was also evaluated in other iVR studies, revealing significant differences among users with varying levels of experience with this technology [58]. These results with few variations between users of different ages and previous iVR trials may be attributed to the simplicity of our iVR experience. Positive results were expected in terms of usability and satisfaction across all age groups, regardless of prior experience with iVR, as the iVR experience was designed to be simple and accessible to all types of audiences. It also reduced age-related differences such as the novelty effect.

Table 2: User results in relation to the different factors, showing both the M and the SD of each factor.

|                         | N  | Cybersickness<br>(M/SD) | Involvement<br>(M/SD) | Adaption/Immersion<br>(M/SD) | Visual Fidelity<br>(M/SD) | Reconstruction questions<br>(M/SD) |
|-------------------------|----|-------------------------|-----------------------|------------------------------|---------------------------|------------------------------------|
| Total                   | 60 | 4.58 / 0.94             | 4.06 / 0.86           | 3.73 / 1.06                  | 4.05 / 0.93               | 4.02 / 0.92                        |
| No iVR Experience       | 34 | 4.56 / 1.05             | 4.10 / 0.86           | 3.67 / 1.06                  | 4.01 / 0.94               | 4.07 / 0.96                        |
| Previous iVR Experience | 26 | 4.62 / 0.80             | 4.00 / 0.87           | 3.81 / 1.05                  | 4.11 / 0.92               | 3.94 / 0.85                        |
| Group Age 1             | 15 | 4.80 / 0.56             | 3.91 / 1.00           | 4.02 / 1.05                  | 4.46 / 0.81               | 3.78 / 1.06                        |
| Group Age 2             | 15 | 4.20 / 1.42             | 3.96 / 0.90           | 3.51 / 1.05                  | 3.71 / 1.01               | 4.07 / 0.78                        |
| Group Age 3             | 15 | 4.60 / 0.91             | 4.23 / 0.72           | 3.84 / 1.09                  | 4.13 / 0.73               | 4.13 / 0.89                        |
| Group Age 4             | 15 | 4.73 / 0.59             | 4.15 / 0.78           | 3.56 / 0.99                  | 3.93 / 1.02               | 4.05 / 0.93                        |

Delving deeper into the differences between the various user-types, a user behavior analysis based on k-means clustering, in which users are grouped into clusters based on response patterns, was also conducted [41]. For the analysis, Questions 1 to 3 were excluded, as they pertained to demographic aspects that would have influenced the composition of the clusters. The remaining questions were analyzed using the Hartigan-Wong algorithm [39].

Figure 11 depicts the Cluster plot on the left-hand side, illustrating the two clearly independent clusters, Cluster 1 (in blue) and Cluster 2 (in green). Both the X and the Y-axis represent the weight of the two dimensions identified for clustering. On the right-hand side, a box plot shows the scores of both clusters for each factor. The Y-axis displays the distribution of the scores, while the X-axis shows each factor divided between the two clusters, with Cluster 1 always on the left and Cluster 2 on the right. Examining the demographic data, Cluster 1 has an average age of 27, with 59% of its members having prior experience in iVR. In contrast, Cluster 2 has an average age of 53, with 41% of its members having prior experience in iVR. The older users of Cluster 2 might therefore have tried out iVR on fewer occasions than the younger members of Cluster 1.

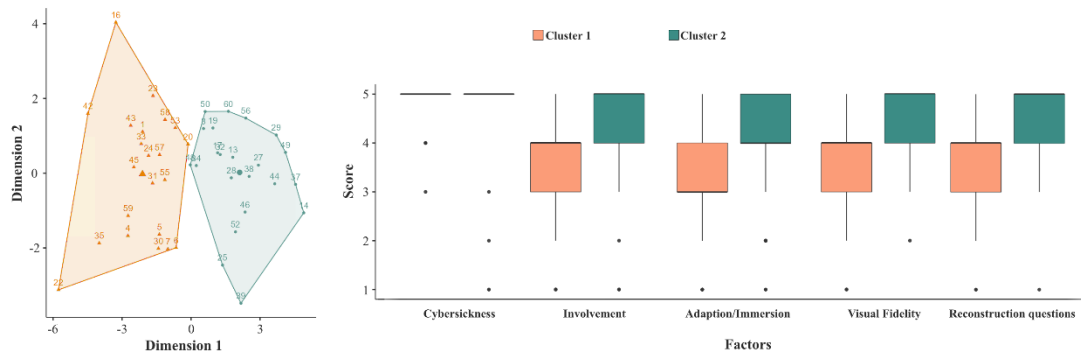


Fig. 11: Cluster Plot (left), box plot with the scores of the two clusters in each factor (right).

As observed, Cluster 1 groups together lower scores across all factors, concentrated around 3 or 4. In contrast, the scores for Cluster 2 (older age group and less experienced in iVR) are concentrated around 4 to 5. The exception is the Cybersickness factor, where both groups have the same score, concentrated around 5. The positive results of both groups were also echoed in previous studies, in which the impact of the novelty effect and age on user behavior was higher among older and less experienced users [58, 67].

The results of this study indicate a very positive response from the sample across all the factors that were evaluated, demonstrating high usability and user satisfaction with both the iVR experience and the reconstructed 3D model. Although no obvious differences were observed between age groups and prior iVR experiences, those differences could be detected using clustering methods, which revealed typical behaviors of such users in similar experiences, with higher results among users with less prior experience in iVR. The lack of clear differences at first glance may be indicative of a well-designed iVR experience for a variety of audiences within musealization contexts. The simple design was intended to mitigate the friction that this technology can cause in uncontrolled environments with diverse user profiles, such as museum exhibitions [10]. The results were highly satisfactory in that regard, although the 3D model has still to be implemented in more complex iVR experiences, so that its potential as a VA may be further explored.

## 7 CONCLUSIONS

The development, assessment, and iVR implementation of a virtual reconstruction of the sculpture of the Isis of Clunia (Spain) from the 2nd c. AD has been presented in this study. The reconstruction procedure of the 3D model utilized close-range photogrammetry to build an initial model. Subsequently, the photogrammetric model was supplemented with historical information through 3D modeling for non-structural restorations and digital sculpting for structural restorations. The model was then optimized through retopology and texture baking. The deviation of the 3D model from the original photogrammetry was few mm and its detail were concentrated in the iconic attributes of the sculpture and the movable, expressive parts, facilitating its animation and its use as a VA with a high LoD. This process resulted in a light 3D model ready for implementation in iVR experiences and with the potential to be used as a VA. In addition, the model is open access and freely downloadable. The procedure executed in this research has yielded satisfactory results. However, a

limitation of this procedure is the loss of fidelity of the generated model in relation to original statue, due to the data acquisition and optimization methods employed.

An explorative iVR experience has been developed to test an initial implementation of the model. Users were able to observe the sculpture in its two states: original and reconstructed. The results of the iVR experience were tested with a sample of 60 people during the ‘White Night’ event at the Museum of Burgos (Spain). The 3D model was well received, and the evaluation yielded very positive results in terms of usability and user satisfaction, for both the 3D model and the iVR experience. Further analysis of the results with clustering methods showed less satisfactory results between young people with previous iVR experience and higher satisfaction among older people who had never experienced iVR before, due in all likelihood to the novelty effect [58]. In any case, the effect was hardly noticeable in the results of both groups, which were very satisfactory. In the future, it is planned to use the model in more complex iVR experiences and to explore its potential as a VA, in addition to assessing the degree of user interaction with users from a wide range of demographics in this more complex experience. Moreover, the development of simpler iVR experiences focused on the Isis of Clunia is also planned as part of the activities of the Museum of Burgos.

## REFERENCES

- [1] Rahman Abidin, Nunuk Suryani, and Sariyatun . 2020. Students’ Perceptions of 360 Degree Virtual Tour-Based Historical Learning About The Cultural Heritage Area of The Kapitan and Al-Munawar Villages in Palembang City. *International Journal of Social Sciences and Management* 7, 3 (July 2020), 105–112. <https://doi.org/10.3126/ijssm.v7i3.29764>
- [2] Francesco Aggogeri, Emmanouil Kontogiorgakis, Emmanouil Zidianakis, Eirini Kontaki, Nikolaos Partarakis, Constantina Manoli, Stavroula Ntoa, and Constantine Stephanidis. 2024. Gamified VR Storytelling for Cultural Tourism Using 3D Reconstructions, Virtual Humans, and 360 • Videos. (2024). <https://doi.org/10.3390/technologies>
- [3] Jaime Alvar and Valentino Gasparini. 2020. The gens isiaca in Hispania. *Contextualizing the Iseum at Italica* (Ausonius Éditions ed.). Ausonius.
- [4] Byron Alvarado Vanegas, Núria Galí-Espelt, and Dolors Vidal-Casellas. 2024. Las nuevas tecnologías de los museos para la visita de sus usuarios: una revisión de la literatura del período pre-COVID-19. *Investigaciones Turísticas* 27 (January 2024), 129–160. <https://doi.org/10.14198/INTURI.23813>
- [5] Christoph Anthes, Rubén Jesús García-Hernández, Markus Wiedemann, and Dieter Kranzlmüller. 2016. State of the art of virtual reality technology. In *IEEE Aerospace Conference Proceedings*, June 27, 2016. IEEE Computer Society. <https://doi.org/10.1109/AERO.2016.7500674>
- [6] María Amparo Arroyo de la Fuente. 2002. EL CULTO ISIACO EN EL IMPERIO ROMANO. *CULTOS DIARIOS Y RITUALES INICIÁTICOS: ICONOGRAFÍA Y SIGNIFICADO*. *Boletín de la Asociación Española de Egiptología* 12 (2002), 207–232.
- [7] Danilo Avola, Luigi Cinque, Gian Luca Foresti, and Marco Raoul Marini. 2023. A novel low cybersickness dynamic rotation gain enhancer based on spatial position and orientation in virtual environments. *Virtual Real* 27, 4 (December 2023), 3191–3209. <https://doi.org/10.1007/s10055-023-00865-1>
- [8] Alberto Balil. 1956. El culto de Isis en España. In *Cuadernos de trabajos de la Escuela Española de Historia y Arqueología en Roma, CSIC - Escuela Española de Historia y Arqueología (EEHAR)* (ed.). 213–224.
- [9] Fabrizio Banfi. 2021. The Evolution of Interactivity, Immersion and Interoperability in HBIM: Digital Model Uses, VR and AR for Built Cultural Heritage. *ISPRS Int J Geoinf* 10, 10 (October 2021), 685. <https://doi.org/10.3390/ijgi10100685>
- [10] Mafkereseb Kassahun Bekele, Roberto Pierdicca, Emanuele Frontoni, Eva Savina Malinverni, and James Gain. 2018. A Survey of Augmented, Virtual, and Mixed Reality for Cultural Heritage. *Journal on Computing and Cultural Heritage* 11, 2 (June 2018), 1–36. <https://doi.org/10.1145/3145534>
- [11] Anton Bogdanovych, Juan Antonio Rodriguez, Simeon Simoff, and Alex Cohen. 2009. Virtual Agents and 3D Virtual Worlds for Preserving and Simulating Cultures. In *Lecture Notes in Computer Science* (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics). 257–271. [https://doi.org/10.1007/978-3-642-04380-2\\_29](https://doi.org/10.1007/978-3-642-04380-2_29)
- [12] Alberto Cannavò, Simona Pacchiotti, Nicola Retta, Martina Terzoli, Roberta Spallone, and Fabrizio Lamberti. 2024. Passive Haptics and Conversational Avatars for Interacting with Ancient Egypt Remains in High-Fidelity Virtual Reality Experiences. *Journal on Computing and Cultural Heritage* 17, 2 (June 2024), 1–28. <https://doi.org/10.1145/3648003>

- [13] Carole Raddato. National Museum of Rome, Baths of Diocletian. Pinterest. Retrieved December 4, 2024 from <https://es.pinterest.com/pin/national-museum-of-rome-baths-of-diocletian--376050637615187263/>
- [14] Joaquín Cerdá-Boluda, Marta C. Mora, Nuria Lloret, Stefano Scarani, and Jorge Sastre. 2024. Design of Virtual Hands for Natural Interaction in the Metaverse. *Sensors* 24, 3 (January 2024), 741. <https://doi.org/10.3390/s24030741>
- [15] Kedong Chai and Yue Li. 2022. Cultural Heritage Assets Optimization Workflow for Interactive System Development. In 2022 IEEE 46th Annual Computers, Software, and Applications Conference (COMPSAC), June 2022. IEEE, 1822–1827. <https://doi.org/10.1109/COMPSAC54236.2022.00290>
- [16] David Checa and Mario Alaguero. 2024. Optimization of a Standalone VR Experience Through User Perception: A Journey to the Hidden Spaces of the Burgos Cathedral. In 2024 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW), March 16, 2024. IEEE, 893–894. <https://doi.org/10.1109/VRW62533.2024.00243>
- [17] David Checa and Andres Bustillo. 2020. A review of immersive virtual reality serious games to enhance learning and training. *Multimed Tools Appl* 79, 9–10 (2020), 5501–5527. <https://doi.org/10.1007/s11042-019-08348-9>
- [18] David Checa and Andres Bustillo. 2020. Advantages and limits of virtual reality in learning processes: Briviesca in the fifteenth century. *Virtual Real* 24, 1 (March 2020), 151–161. <https://doi.org/10.1007/s110055-019-00389-7>
- [19] Mi-Hyun Choi, Kyu-Young Kang, Tae-Hoon Lee, and Jin-Seung Choi. 2024. Correlations between SSQ Scores and ECG Data during Virtual Reality Walking by Display Type. *Applied Sciences* 14, 5 (March 2024), 2123. <https://doi.org/10.3390/app14052123>
- [20] Ami Chopine. 2011. 3D Art Essentials The Fundamentals of 3D Modeling, Texturing, and Animation (1st ed.). Elsevier, Oxford.
- [21] Emanuel Demetrescu and Daniele Ferdani. 2021. From Field Archaeology to Virtual Reconstruction: A Five Steps Method Using the Extended Matrix. *Applied Sciences* 11, 11 (June 2021), 5206. <https://doi.org/10.3390/app11115206>
- [22] Hugh Denard. 2012. A New Introduction to The London Charter. In *Paradata and Transparency in Virtual Heritage Digital Research in the Arts and Humanities Series*. Ashgate, 57–71. Retrieved from <http://www.londoncharter.org>
- [23] Wentao Deng, Wei Ke, Zhongmin Deng, and Xungai Wang. 2024. Virtual design of woven fabrics based on parametric modeling and physically based rendering. *Computer-Aided Design* 173, (August 2024), 103717. <https://doi.org/10.1016/j.cad.2024.103717>
- [24] A. Dhanda, M. Reina Ortiz, A. Weigert, A. Paladini, A. Min, M. Gyi, S. Su, S. Fai, and M. Santana Quintero. 2019. RECREATING CULTURAL HERITAGE ENVIRONMENTS FOR VR USING PHOTOGRAMMETRY. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLII-2/W9, 2/W9* (January 2019), 305–310. <https://doi.org/10.5194/isprs-archives-XLII-2-W9-305-2019>
- [25] Manuel Drago Díaz alemán. 2023. Retopología de mallas aplicada a modelos 3D de patrimonio cultural para la mejora de la visualización interactiva en realidad virtual y realidad aumentada. *Ge-conservacion* 24, 1 (October 2023), 87–98. <https://doi.org/10.37558/gec.v24i1.1147>
- [26] Andrea Dordio, Eva Lanchó, María José Merchán, and Pilar Merchán. 2024. Cultural Heritage as a Didactic Resource through Extended Reality: A Systematic Review of the Literature. *Multimodal Technologies and Interaction* 8, 7 (July 2024), 58. <https://doi.org/10.3390/mti8070058>
- [27] Clark Erickson, Emiliya Al Yafei, Josh Nadel, Youssef Victor, Ikuomor Mabel Ogiriki, and Norman Badler. 2018. Re-creating pre-columbian life in the baures region of the bolivian amazon. In *Proceedings - 2018 20th Symposium on Virtual and Augmented Reality, SVR 2018*, October 01, 2018. Institute of Electrical and Electronics Engineers Inc., 253–257. <https://doi.org/10.1109/SVR.2018.00043>
- [28] Lorena Espina-Romero and Jesús Guerrero-Alcedo. 2022. Fields Touched by Digitalization: Analysis of Scientific Activity in Scopus. *Sustainability* 14, 21 (November 2022), 14425. <https://doi.org/10.3390/su142114425>
- [29] Leonarda Fazio, Mauro Lo Brutto, Sara Gonizzi Barsanti, and Saverio Giulio Malatesta. 2022. The Virtual Reconstruction of the Aesculapius and Hygeia Statues from the Sanctuary of Isis in Lilybaeum: Methods and Tools for Ancient Sculptures’ Enhancement. *Applied Sciences* 12, 7 (March 2022), 3569. <https://doi.org/10.3390/app12073569>
- [30] Shaun Foster and David Halbshtein. 2014. Integrating 3D Modeling, Photogrammetry and Design. Springer London, London. <https://doi.org/10.1007/978-1-4471-6329-9>
- [31] Francesco Gabellone. 2015. Virtual Environments and Technological Solutions for an enriched viewing of historic and archeological contexts. In *First Olympia Seminar, 2015*. 223–232. Retrieved from <https://www.researchgate.net/publication/303803204>
- [32] İsmail Çağrı Gençtürk, Bilal Erkek, and Ekrem Ayyıldız. 2025. Integrating Photogrammetric 3D City Models into Virtual Reality: A Methodological Approach Using Unreal Engine. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLVIII-M-6–2025, M-6–2025* (May 2025), 353–358. <https://doi.org/10.5194/isprs-archives-XLVIII-M-6-2025-353-2025>
- [33] Francesco Gherardini, Mattia Santachiara, and Francesco Leali. 2018. 3D Virtual Reconstruction and Augmented Reality Visualization of Damaged Stone Sculptures. *IOP Conf Ser Mater Sci Eng* 364, 1 (June 2018), 012018. <https://doi.org/10.1088/1757-899X/364/1/012018>

- [34] Francesco Gherardini, Mattia Santachiara, and Francesco Leali. 2019. Enhancing heritage fruition through 3D virtual models and augmented reality: an application to Roman artefacts. *Virtual Archaeology Review* 10, 21 (July 2019), 67. <https://doi.org/10.4995/var.2019.11918>
- [35] Google Arts & Culture. File Isis Museum of Naples. Retrieved October 28, 2024 from [https://artsandculture.google.com/asset/statua-di-isiside-fortuna/OwGvROavgkj\\_HQ?hl=en](https://artsandculture.google.com/asset/statua-di-isiside-fortuna/OwGvROavgkj_HQ?hl=en)
- [36] Google Arts & Culture. File Isis National Roman Museum of the Baths of Diocletian . Retrieved October 30, 2024 from <https://artsandculture.google.com/asset/statue-of-the-goddess-isis/DQF77-3ed3ja4w>
- [37] Gryffindor. Archivio:Isis - Vienna.jpg. Wikimedia Commons. Retrieved December 4, 2024 from [https://es.m.wikipedia.org/wiki/Archivo:Isis\\_-\\_Vienna.jpg](https://es.m.wikipedia.org/wiki/Archivo:Isis_-_Vienna.jpg)
- [38] Jassim Happa, Mark Mudge, Kurt Debatista, Alessandro Artusi, Alexandrino Gonçalves, and Alan Chalmers. 2010. Illuminating the past: state of the art. *Virtual Real* 14, 3 (September 2010), 155–182. <https://doi.org/10.1007/s10055-010-0154-x>
- [39] J. A. Hartigan and M. A. Wong. 1979. Algorithm AS 136: A K-Means Clustering Algorithm. *Appl Stat* 28, 1 (1979), 100. <https://doi.org/10.2307/2346830>
- [40] Oliver Hauck and Piotr Kuroczyński. 2014. Cultural Heritage Markup Language How to Record and Preserve 3D Assets of Digital Reconstruction. In *International Conference on Cultural Heritage and New Technologies*, 2014. . Retrieved from <http://architosh.com/2014/06/in-depth-the-new-and-dynamic-formz-8/3/>
- [41] C Hennig, M Meila, F Murtagh, and R Rocci. 2015. *Handbook of Cluster Analysis*. New York.
- [42] Mateusz Janiszewski, Masoud Torkan, Lauri Uotinen, and Mikael Rinne. 2022. Rapid Photogrammetry with a 360-Degree Camera for Tunnel Mapping. *Remote Sens (Basel)* 14, 21 (October 2022), 5494. <https://doi.org/10.3390/rs14215494>
- [43] Stavros Kateros, Stylianos Georgiou, Margarita Papaefthymiou, George Papagiannakis, and Michalis Tsioumas. 2015. A Comparison of Gamified, Immersive VR Curation Methods for Enhanced Presence and Human-Computer Interaction in Digital Humanities. *International Journal of Heritage in the Digital Era* 4, 2 (June 2015), 221–233. <https://doi.org/10.1260/2047-4970.4.2.221>
- [44] Thomas Keep. 2022. The Mernda VR Project: The Creation of a VR Reconstruction of an Australian Heritage Site. *Journal of Computer Applications in Archaeology* 5, 1 (November 2022), 238–254. <https://doi.org/10.5334/jcaa.91>
- [45] Kaitlyn Kingsland. 2020. Comparative analysis of digital photogrammetry software for cultural heritage. *Digital Applications in Archaeology and Cultural Heritage* 18, (September 2020), e00157. <https://doi.org/10.1016/j.daach.2020.e00157>
- [46] Chairi Kiourt, George Pavlidis, Anestis Koutsoudis, and Dimitis Kalles. 2017. Multi-agents based virtual environments for cultural heritage. In *2017 XXVI International Conference on Information, Communication and Automation Technologies (ICAT)*, October 2017. IEEE, 1–6. <https://doi.org/10.1109/ICAT.2017.8171602>
- [47] Chairi Kiourt, Helena G. Theodoropoulou, Anestis Koutsoudis, Jorgos Alexis Ioannakis, George Pavlidis, and Dimitris Kalles. 2020. Exploiting Cross-Reality Technologies for Cultural Heritage Dissemination. In *Applying Innovative Technologies in Heritage Science, Communication and Knowledge Technologies* George Pavlidis (Athena – Research and Innovation Center in Information (ed.). 85–108. <https://doi.org/10.4018/978-1-7998-2871-6.ch005>
- [48] Arno Knapitsch, Jaesik Park, Qian-Yi Zhou, and Vladlen Koltun. 2017. Tanks and temples: Benchmarking Large-Scale Scene Reconstruction. *ACM Trans Graph* 36, 4 (August 2017), 1–13. <https://doi.org/10.1145/3072959.3073599>
- [49] Daniel Kükenbrink, Mauro Marty, Ruedi Bösch, and Christian Ginzler. 2022. Benchmarking laser scanning and terrestrial photogrammetry to extract forest inventory parameters in a complex temperate forest. *International Journal of Applied Earth Observation and Geoinformation* 113, (September 2022). <https://doi.org/10.1016/j.jag.2022.102999>
- [50] Eugene Kukshinov, Joseph Tu, Kata Szita, Kaushal Senthil Nathan, and Lennart E. Nacke. 2024. “Never The Same”: Systematic Analysis of the Methodological Issues in the Presence Studies That Employ Questionnaires. In *Extended Abstracts of the CHI Conference on Human Factors in Computing Systems*, May 11, 2024. ACM, New York, NY, USA, 1–7. <https://doi.org/10.1145/3613905.3651074>
- [51] Antoine Laurent, Benjamin Couprie, Baptiste Brument, Jean Mélou, Yvain Quéau, Carole Fritz, and Jean-Denis Durou. 2025. Combining geometric and photometric 3D reconstruction techniques for cultural heritage. *J Cult Herit* 73, (May 2025), 43–51. <https://doi.org/10.1016/j.culher.2025.02.013>
- [52] Kenneth R. Leitch and Malcolm B. Coon. 2012. Noncontact Modeling of Structures Using Close-Range Digital Photogrammetry. *Practice Periodical on Structural Design and Construction* 17, 4 (November 2012), 161–165. [https://doi.org/10.1061/\(ASCE\)SC.1943-5576.0000124](https://doi.org/10.1061/(ASCE)SC.1943-5576.0000124)
- [53] J. Liu, D. Willkens, C. López, L. Cortés-Meseguer, J. L. García-Valdecabres, P. A. Escudero, and S. Alathamneh. 2023. COMPARATIVE ANALYSIS OF POINT CLOUDS ACQUIRED FROM A TLS SURVEY AND A 3D VIRTUAL TOUR FOR HBIM DEVELOPMENT. *The*

- International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLVIII-M-2–2023, (June 2023), 959–968. <https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-959-2023>
- [54] Gonzalo Andrés López and David Checa Cruz. 2021. Experiences of Knowledge Transfer on Industrial Heritage Using Games, Storytelling, and New Technologies. *Journal on Computing and Cultural Heritage* 14, 2 (June 2021), 1–26. <https://doi.org/10.1145/3424951>
- [55] Octavian M. Machidon, Mihai Duguleana, and Marcello Carrozzino. 2018. Virtual humans in cultural heritage ICT applications: A review. *J Cult Herit* 33, (September 2018), 249–260. <https://doi.org/10.1016/j.culher.2018.01.007>
- [56] Andrea Marraffa and Francesca Fatta. 2021. The digital anastylosis and the semantic segmentation: The case of the Magna Graecia masks in the Mediterranean area. *DISEGNARECON* 14, 26 (2021). <https://doi.org/10.20365/disegnarecon.26.2021.12>
- [57] María Antonia Díaz Mendoza, Emiro De La Hoz Franco, and Jorge Elicer Gómez Gómez. 2023. Technologies for the Preservation of Cultural Heritage—A Systematic Review of the Literature. *Sustainability* 15, 2 (January 2023), 1059. <https://doi.org/10.3390/su15021059>
- [58] Ines Miguel-Alonso, David Checa, Henar Guillen-Sanz, and Andres Bustillo. 2024. Evaluation of the novelty effect in immersive Virtual Reality learning experiences. *Virtual Real* 28, 1 (March 2024), 27. <https://doi.org/10.1007/s10055-023-00926-5>
- [59] Elena Muñoz Grijalvo. 2021. El lugar del culto de Isis en las ciudades de la península ibérica. *Hisp Sacra* 73, 147 (June 2021), 11–17. <https://doi.org/10.3989/hs.2021.001>
- [60] Alejandro Muñoz-Muñoz, Diego Fernández-Sánchez, Eduardo Vijande-Vila, Serafin Becerra-Martín, Juan Jesús Cantillo-Duarte, Salvador Domínguez-Bella, Virgilio Martínez Enamorado, Francisca Rengel Castro, Pedro Cantalejo Duarte, María del Mar Espejo-Herrerías, José Suárez-Padilla, Juan Antonio Martín-Ruiz, and José Ramos-Muñoz. 2023. Application of photogrammetry and laser scanner on the Bronze Age structures of the Castillejos de Luna cist tomb necropolis (Pizarra, Spain). *Virtual Archaeology Review* 14, 29 (July 2023), 26–44. <https://doi.org/10.4995/var.2023.19126>
- [61] Sander Münster. 2022. Digital 3D Technologies for Humanities Research and Education: An Overview. *Applied Sciences* 12, 5 (February 2022), 2426. <https://doi.org/10.3390/app12052426>
- [62] Sander Münster, Wolfgang Hegel, and Cindy Kröber. 2016. A model classification for digital 3D reconstruction in the context of humanities research. In *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 2016. Springer Verlag, 3–31. [https://doi.org/10.1007/978-3-319-47647-6\\_1](https://doi.org/10.1007/978-3-319-47647-6_1)
- [63] Museo del Prado. Isis File Museo del Prado. Retrieved October 28, 2024 from <https://www.museodelprado.es/coleccion/obra-de-arte/la-diosa-isis-clunia/70b68a29-5ee8-40e0-b442-a16774215a2a>
- [64] Museum of Art History in Vienna. File Isis Museum of Art History in Vienna. Retrieved October 28, 2024 from [www.khm.at/en/object/50667/](http://www.khm.at/en/object/50667/)
- [65] Cleopas Njerekai. 2019. An application of the virtual reality 360° concept to the Great Zimbabwe monument. *Journal of Heritage Tourism* 15, 5 (2019), 567–579. <https://doi.org/10.1080/1743873X.2019.1696808>
- [66] Miloš Obradović, Ivana Vasiljević, Isidora Đurić, Jelena Kićanović, Vesna Stojaković, and Ratko Obradović. 2020. Virtual Reality Models Based on Photogrammetric Surveys—A Case Study of the Iconostasis of the Serbian Orthodox Cathedral Church of Saint Nicholas in Sremski Karlovci (Serbia). *Applied Sciences* 10, 8 (April 2020), 2743. <https://doi.org/10.3390/app10082743>
- [67] Alfonsina Pagano, Augusto Palombini, Guido Bozzelli, Maurizio De Nino, Ivana Cerato, and Stefano Ricciardi. 2020. ArkaeVision VR game: User experience research between real and virtual paestum. *Applied Sciences (Switzerland)* 10, 9 (May 2020). <https://doi.org/10.3390/app10093182>
- [68] András Patay-Horváth. 2014. The virtual 3D reconstruction of the east pediment of the temple of Zeus at Olympia an old puzzle of classical archaeology in the light of recent technologies. *Digital Applications in Archaeology and Cultural Heritage* 1, 1 (2014), 12–22. <https://doi.org/10.1016/j.daach.2013.06.001>
- [69] Mark Peercy, John Airey, and Brian Cabral. 1997. Efficient bump mapping hardware. In *Proceedings of the 24th annual conference on Computer graphics and interactive techniques - SIGGRAPH '97, 1997*. ACM Press, New York, New York, USA, 303–306. <https://doi.org/10.1145/258734.258873>
- [70] Red Digital de Colecciones de Museos de España. File Isis Museum of Burgos. Retrieved October 28, 2024 from <https://ceres.mcu.es/pages/Main?id=121907&inventory=27&table=FMUS&museum=MBU>
- [71] Fabio Remondino. 2011. Heritage Recording and 3D Modeling with Photogrammetry and 3D Scanning. *Remote Sens (Basel)* 3, 6 (May 2011), 1104–1138. <https://doi.org/10.3390/rs3061104>
- [72] Fabio Remondino and Sabry El-Hakim. 2006. Image-based 3D Modelling: A Review. *The Photogrammetric Record* 21, 115 (September 2006), 269–291. <https://doi.org/10.1111/j.1477-9730.2006.00383.x>

- [73] Fabio Remondino, Ali Karami, Ziyang Yan, Gabriele Mazzacca, Simone Rigon, and Rongjun Qin. 2023. A Critical Analysis of NeRF-Based 3D Reconstruction. *Remote Sens (Basel)* 15, 14 (July 2023), 3585. <https://doi.org/10.3390/rs15143585>
- [74] A. Rodriguez, J. F. Chuchiak, H. B. Erickson, and P. V. Ballicu. 2021. The great “auto de fe” at santiago de los caballeros, or how to achieve historical empathy with cultural heritage through virtual reality. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, September 10, 2021. International Society for Photogrammetry and Remote Sensing, 633–640. <https://doi.org/10.5194/isprs-archives-XLVI-M-1-2021-633-2021>
- [75] Bruno Rodriguez-Garcia, Henar Guillen-Sanz, David Checa, and Andres Bustillo. 2024. A systematic review of virtual 3D reconstructions of Cultural Heritage in immersive Virtual Reality. *Multimed Tools Appl* (April 2024). <https://doi.org/10.1007/s11042-024-18700-3>
- [76] Bruno Rodriguez-Garcia, Ines Miguel-Alonso, Henar Guillen-Sanz, and Andres Bustillo. 2025. LoDCalculator: A level of detail classification software for 3D models in the Blender environment. *SoftwareX* 30, (May 2025), 102107. <https://doi.org/10.1016/j.softx.2025.102107>
- [77] Silvia Rossi, Irene Viola, Laura Toni, and Pablo Cesar. 2015. From 3-DoF to 6-DoF: New Metrics to Analyse Users Behaviour in Immersive Applications. *Journal of Latex Class Files* 14 14, 8 (December 2015). <https://doi.org/10.48550/arXiv.2112.09402>
- [78] Sailko. File:Iside di età adrianea, da villa adriana.JPG. Wikimedia Commons. Retrieved December 4, 2024 from [https://commons.wikimedia.org/wiki/File:Iside\\_di\\_et%C3%A0\\_adrianea,\\_da\\_villa\\_adriana.JPG](https://commons.wikimedia.org/wiki/File:Iside_di_et%C3%A0_adrianea,_da_villa_adriana.JPG)
- [79] Remigio Salomón. 1853. Estatua romana de Clunia. Retrieved September 10, 2024 from [https://bibliotecavirtualmadrid.comunidad.madrid/bvmadrid\\_publicacion/es/catalogo\\_imagenes/grupo.do?path=1031511](https://bibliotecavirtualmadrid.comunidad.madrid/bvmadrid_publicacion/es/catalogo_imagenes/grupo.do?path=1031511)
- [80] Swati Shilaskar, Shripad Bhatlawande, Sourjadip Pramanik, Anshul Surana, Jyoti Madake, and Anjali Solanke. 2025. A scalable structure-from-motion framework for efficient 2D-to-3D reconstruction of historical artifacts. *Journal of Integrated Science and Technology* 13, 5 (April 2025). <https://doi.org/10.62110/sciencein.jist.2025.v13.1120>
- [81] Sovrintendenza Capitolina ai Beni Culturali. File Isis Capitoline Museum in Rome . Retrieved October 28, 2024 from <http://capitolini.info/scu00744/?lang=en>
- [82] R. Spallone, F. Lamberti, M. Guglielminotti Trivel, F. Ronco, and S. Tamantini. 2021. 3D RECONSTRUCTION AND PRESENTATION OF CULTURAL HERITAGE: AR AND VR EXPERIENCES AT THE MUSEO D’ARTE ORIENTALE DI TORINO. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLVI-M-1–2021, M-1–2021* (August 2021), 697–704. <https://doi.org/10.5194/isprs-archives-XLVI-M-1-2021-697-2021>
- [83] Nataska Statham. 2020. Use of Photogrammetry in Video Games: A Historical Overview. *Games Cult* 15, 3 (May 2020), 289–307. <https://doi.org/10.1177/1555412018786415>
- [84] Stella Sylaiou and Christos Fidas. 2022. Virtual Humans in Museums and Cultural Heritage Sites. *Applied Sciences* 12, 19 (October 2022), 9913. <https://doi.org/10.3390/app12199913>
- [85] Yongdong Tong, Youzhen Cai, Austin Nevin, and Qinglin Ma. 2023. Digital technology virtual restoration of the colours and textures of polychrome Bodhidharma statue from the Lingyan Temple, Shandong, China. *Herit Sci* 11, 1 (December 2023). <https://doi.org/10.1186/s40494-023-00858-y>
- [86] Tomas Trescak and Anton Bogdanovych. 2017. Case-based planning for large virtual agent societies. In *Proceedings of the ACM Symposium on Virtual Reality Software and Technology, VRST, November 08, 2017. Association for Computing Machinery*. <https://doi.org/10.1145/3139131.3139155>
- [87] Mariapina Trunfio and Salvatore Campana. 2020. A visitors’ experience model for mixed reality in the museum. *Current Issues in Tourism* 23, 9 (May 2020), 1053–1058. <https://doi.org/10.1080/13683500.2019.1586847>
- [88] Sara Vlahovic, Mirko Suznjevic, and Lea Skorin-Kapov. 2022. A survey of challenges and methods for Quality of Experience assessment of interactive VR applications. *Journal on Multimodal User Interfaces* 16, 3 (September 2022), 257–291. <https://doi.org/10.1007/s12193-022-00388-0>
- [89] Sophia Vu, Daniel Clibum, Jennifer Helgren, Joshua Slayers, Keely Canniff, Andrew Johnson, Mary Miliken, Tyler Reardon, Kyle Sabbatino, and Alicia Stephan. 2018. Recreating Little Manila through a Virtual Reality Serious Game. In *2018 3rd Digital Heritage International Congress (DigitalHERITAGE) held jointly with 2018 24th International Conference on Virtual Systems & Multimedia (VSMM 2018)*, 2018. 1–4. <https://doi.org/10.1109/DigitalHeritage.2018.8810082>
- [90] Bob G. Witmer, Christian J. Jerome, and Michael J. Singer. 2005. The Factor Structure of the Presence Questionnaire. *Presence: Teleoperators and Virtual Environments* 14, 3 (June 2005), 298–312. <https://doi.org/10.1162/105474605323384654>
- [91] Bob G. Witmer and Michael J. Singer. 1998. Measuring Presence in Virtual Environments: A Presence Questionnaire. *Presence: Teleoperators and Virtual Environments* 7, 3 (June 1998), 225–240. <https://doi.org/10.1162/105474698565686>

- [92] Li Yang, Nankai Cheng, Puyuan Jiang, and Paulo Noriega. 2024. Virtual Museums: State of the Art, Trends, and Challenges. In *Communications in Computer and Information Science*. Springer Science and Business Media Deutschland GmbH, 226–237. [https://doi.org/10.1007/978-3-031-61966-3\\_26](https://doi.org/10.1007/978-3-031-61966-3_26)
- [93] Joel Qi Hong Yap, Zilmiyah Kamble, Adrian T.H. Kuah, and Denis Tolkach. 2024. The impact of digitalisation and digitisation in museums on memory-making. *Current Issues in Tourism* 27, 16 (August 2024), 2538–2560. <https://doi.org/10.1080/13683500.2024.2317912>
- [94] María José Zaparaín Yáñez. 2022. ESTATUA DE ISIS. CLUNIA. Burgos. Retrieved September 10, 2024 from <https://catedrapatrimonioubu.com/project/estatua-de-isis/>
- [95] Chen Zhang, Biao He, Renzhong Guo, and Ding Ma. 2023. When a tree model meets texture baking: an approach for quality-preserving lightweight visualization in virtual 3D scene construction. *Int J Digit Earth* 16, 1 (October 2023), 645–670. <https://doi.org/10.1080/17538947.2023.2177758>
- [96] Fan Zhang, Xianfeng Huang, Wei Fang, Zhichao Zhang, Deren Li, and Yixuan Zhu. 2015. Texture reconstruction of 3D sculpture using non-rigid transformation. *J Cult Herit* 16, 5 (September 2015), 648–655. <https://doi.org/10.1016/j.culher.2014.11.004>