# Digitalization and 3D documentation techniques applied to two pieces of Visigothic sculptural heritage in Merida through structured light scanning

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## ABSTRACT

Technological advancements have a great impact on the dissemination and understanding of the cultural heritage reality due to innovative techniques. These innovations are based on high-precision and high-resolution technologies that allow for the geometric documentation of any object within the fields of history and the arts. Through these techniques, new proposals may be studied and objects can be placed in any historical context. Three-dimensional (3D) digitization allows obtaining a digital three-dimensional model, which can be handled virtually and recreated at any historical period, enabling the conservation and safeguarding of the cultural heritage. Society currently demands new visualisation techniques that allow interacting with the architectural and artistic heritage, which have been applied in numerous virtual reconstructions of historical sites or singular archaeological pieces.

This project allowed us to geometrically document a reused piece with two surfaces (shield and columns) and a plaque of the city of Merida, using a structured light scanner from a theoretical-practical perspective. The 3D virtual reconstruction of the pieces was accomplished within this study. The generation of QR codes enabled the interactive display of the heritage pieces. Likewise, a proposal was made to reuse the aforementioned pieces through virtual archaeology. The initial hypothesis is based on the possible existence of a Visigothic niche as an original form. This research reports significant advances in the conservation and exploitation of the cultural heritage.

## CCS CONCEPTS

Modelling methodologies / Model verification and validation / Image processing

**KEYWORDS**
Three-dimensional geometric documentation, structured light scanning, virtual archaeology, cultural heritage, 3D reconstruction, digital conservation technique.

# 1 Introduction:

Art History is defined as "the graphic-verbal science of excellence" [1]. The scientific study of art is usually assisted by numerous illustrations, photographs and drawings, which accompany the text, serving as an indispensable support. It is important to make use of the enormous amount of information provided by graphic expression when researching past civilizations [2], as it facilitates the interpretation of graphically represented projects [3]. Graphic documentation is a perfect complement to the analysis of the reutilisation of pieces throughout the history of human plastic expression. The existence of graphic studies, with images and sketches from a graphic perspective, facilitates the interpretation of heritage and its conservation [4,5]. As a process in Art History, reutilisation has produced important phenomena of acculturation and decontextualisation of pieces, which often makes it difficult to document and date them [6-8].

There are techniques to preserve the cultural architectural heritage [9]. Structured light scanning, via light encoding techniques, is a very successful form of digitization of archaeological pieces [3,10-11]. The different technologies available for the conservation and documentation of artistic pieces are tools that help to better define the culture and art expression of the analysed objects [4,5]. There are two crucial documents that approach exclusively the digital visualisation of heritage: the London Charter [12] and the Seville Principles [13]. Additionally, there are other works focused on the 3D visualisation of heritage, such as some relevant ICOMOS and UNESCO documents [14]. Likewise, the dissemination of the results using innovative techniques, such as virtual visits through QR codes, created by Denso Wave in 1994, makes new advances available for the tourism and trade sectors. QR codes have been widely used for commercial products and in the tourism sector due to its technological attractiveness and its great storage capacity [15].

## 1.1 Research aim

This research project consisted in the 3D scanning of two specific pieces and their three-dimensional representation for virtual visualisation, as an innovative technique for cultural conservation purposes [16]. Both pieces belong to the hosting site of the Visigothic Collection of the National Museum of Roman Art (MNAR), which is located in the Church of Santa Clara in Merida (Spain), and is one of the most important examples of Visigothic art in the world [17]. The first piece is a plaque identified as CE00470, while the second piece, identified as CE00548, is a reutilisation piece, thus it is carved on both sides. On the front side there is a Roman shield, and on the back side there are two columns. The working hypothesis states that the plaque (CE00470) and the reutilised piece of two surfaces (shield and columns) (CE00548) originally formed a Visigothic niche constituted by two superimposed blocks. The aim of this project was to digitally preserve the architectural pieces, capture their geometric documentation and display the 3D model of the final structure in an interactive way, after formulating a hypothesis. The geometric documentation was obtained using a structured light scanner. 3D scanning provides a faithful three-dimensional model of the original object with submillimetric precision, enhanced through computer graphics [18,19], which show a complete interactive 3D visualisation system. Future researchers in the field of art and humanities will have access to digital models, close to reality, which will allow them to continue advancing their research [20,21].

## 1.2 Overview of Virtual Archaeology

The techniques for the computer graphic representation of heritage are innovative technologies with respect to the traditional analogical drawing representations, which have not changed since ancient times [22]. The codification of the conical perspective, attributed to architect Brunelleschi and theorist Alberti [23], was one of the phenomena that revolutionised graphic representation at different levels. For example, authors such as Almeida-Olmedo [23] identified drawings of Paollo Ucello representing a goblet (c. 1450), which appears to be made of a polyhedral mesh provided by a framework of lines, similar to the wire structure of the meshes generated today to recreate 3D models.

The interest in the graphic representation of monuments and archaeological pieces using computers is not recent. The first traces of the use of virtual representation systems appear in a study conducted by the IBM UK Scientific Centre, in which the work carried out on the Old Cathedral of Winchester by Andrew G.N. Walter and Mike Stanley stands out [24]. Subsequently, Paul Reilly studied data visualisation in archaeology [25] and virtual archaeology [26], with the latter being the first study to use the term "virtual archaeology" as an interpretation system. Forte [27] raised interesting questions about the possible use of virtual models to verify, epistemologically, some data in architecture, material culture and terrain topography. As a result of these first attempts, there was an emergence of projects that exploited the possibilities offered by virtual reality for the documentation and dissemination of heritage [28]. Simultaneously, new studies explored the fact that the virtual model could replace the real one in virtual archaeology [29]. The development of new technologies for geometric documentation, such as digital photogrammetry with multiple images and structured light scanning [10], allows results to evolve and improve, generating models with submillimetric precision [11,30].

## 1.3 History of the graphic representation of Visigothic sculpture

Up to date, Visigothic sculpture has had little graphic representation, unlike the gold and silverware and ceramics of the same period [28]. The representation of some of the most distinctive Visigothic archaeological elements are found in the traveller's engravings made by Laborde [29]. Then, in 1877, José Amador de los Ríos published a monograph of the "Latin-Byzantine Monuments", the first historiographic document that reveals scientific interest in the Visigothic past of the city of Merida. De los Ríos [30] chronologically framed the artistic scope of the Visigoths under the term "Latin-Byzantine".

Various projects related to Visigothic sculpture have been published in scientific literature over the years. However, there are not many examples of drawn graphic representations, especially in the field of sculpture [34]. The most common graphic representations are those related to architecture, blueprints and section views, which shows the complex dimension of Visigothic architecture [35]. The first reference to the systematised study of the Visigothic period appears in the chapter on Visigothic art [36]. Schlunk's volume does not include a large number of drawings, although it does stand out for the high quality of its photographs. Later, Schlunk published his work: "Byzantinische Bauplastik aus Spanien" [37], where some very interesting drawings can be found.

The next great milestone in the graphic representation of Visigothic sculpture was achieved by Professor María Cruz Villalón with her doctoral thesis "Mérida Visigoda" [38]. This research stands out for its eminent graphic feature, where more than 400 ink drawings and photographs are represented to analyse the Visigothic sculptural remains available at that time. This was followed by the publication of other Visigothic research topics in the 1990s, through critical reviews in the "Anejos de A EspA XXIII, 2000". These annexes have valuable graphic representations [39]. Since the 2000's, other studies have been published, such as the work of Sanna [40], who then published his Thesis in Byzantine Influences in Visigothic Sculpture [41], in which some excellent photographs are shown.

Concerning the graphic representation of Visigothic art, some shortcomings have been detected. The most used method to represent Visigothic sculptural pieces has been black and white photography [31]. The drawings are usually of an informative nature, and researchers use them to improve the interpretation of ornamental and decorative elements [42]. Most of the examples that have been analysed lack scales or reference elements that would allow them to confer a metric nature. There are no known examples where the pieces are represented with plan, elevation and section view formats, or some three-dimensional representation of them.

# 2 Material and methods

## 2.1 Materials

A high-resolution and high-precision Mephisto CX (4ddynamics®) structured light scanner was used as one of the latest generation techniques to geometrically document the pieces [43]. This scanner is not compact, but consists of several pieces of equipment, hence the importance of calibrating them as a whole. The technical specifications of the structured light scanner are:

- High geometric resolution of 1024 x 768 in 8 bits, with a texture camera support of a maximum of 12.4 megapixels.
- The projector is an Optoma DLP EX 531pEW536, which projects the geometric pattern onto the object. The optimal distance for information acquisition ranges from 0.7 to 0.3 metres. The information acquisition time ranges from 0.3 to 1.5 seconds. It provides an accuracy of 0.15 mm on average between points.
- A FireWire camera to capture the geometry of the object.
- A Canon SLR camera to perform the texturing tasks.
- A computer with Mephisto 3.0. software (4ddynamics®), to send the capture orders and carry out the parameters configuration.
- As for the computer equipment, for data collection and field work, an HP ProBook 4730s portable workstation was used, and for the post processing of the files, an Alienware 14 portable workstation was used, with Mephisto 3.0 and MephistoProcess 1.2 software (4ddynamics®).
- Free 3D modelling software Meshlab 1.2 and Blender 2.82.
- Software with an educational license 3DReshaper and SketchUp 2018.

## 2.2 Methodology

Geometric documentation of heritage using innovative engineering design techniques requires extensive research. To this end, numerous examples are studied where the technique and methodology are similar to the one applied in the present study. Those that reflect a faithful comparison of their evolution stand out [44-46]. The purpose of geometric documentation techniques is to capture the shape, geometry in the coordinate axes (xyz) and colour characteristics (according to the RGB model) of a volume or environment, with the aim of obtaining a three-dimensional model of it with sub-millimetric precision [47]. The information obtained is translated into a point cloud (xyz, RGB) that takes significant spatial values. Subsequently, a cloud of points is subjected to a post-process with generally long times, to obtain the desired result in the form of a 3D model [48]. Nowadays, there are systems that meet the requirements of geometric accuracy, which are also easy to use and provide high-quality results [49]. Table 1 shows the working methodology for obtaining a 3D model of the scanned parts with sub-millimetric accuracy.

This methodology is based on the previous study of the historical-artistic field of the pieces. As in Georgopoulos et al., [50], the work flows are established both theoretically (through virtual archaeology) and practically (using a structured light scanner). The viewing programmes used are free of charge, and guarantee easy and agile viewing that exceeds the minimum quality standards currently demanded by society. In our case, the particular feature that stands out is the speed of data collection in this field. The difficulties in the process of 3D digitization (field work) lie in the large dimensions of the shield and the consequent lack of manoeuvrability, as well as the difficulty in accessing the back of the plaque, as it remains fixed to a pedestal attached to the wall [51]. Some authors propose solutions to scan the inaccessible parts through the use of mirrors, which is not considered as a solution in our case, since the structured light scanner does not work well with mirrors [3].

The post-processing allows the 3D model of the pieces to be configured. Obtaining their geometry was essential, since both pieces stand out for their use and reusability [52]. Subsequently, a hypothesis was formulated and a new intermediate piece modelled on purpose as an extension of the reused 2-sided piece (shield and columns) (CE00548, hereinafter ‘x’).

Finally, the 3D modelling spreading, as a result of the merging of the three pieces, was conducted on-line for free in an interactive way. Likewise, a hypothesis of the physical environment and a potential location of the resulting Visigothic niche is shown by means of a virtual visit. Both results are available through QR codes. Sketchfab was the on-line platform used to visualise the combination of the pieces.

**Table 1. Description of the work-tasks.**

| | |
|---|---|
| Pre-inspection | Visit to Santa Clara |
| | Analysis of the problems |
| | Proposal of solutions |
| Field work | Light preparation |
| | Equipment Calibration |
| | Scanning - Data collection |
| | On-the-spot check |
| Post-Process | Registration, cleaning and filtering |
| | Mesh optimisation |
| | 3D modelling and volume creation |
| | Defining the ‘x’ piece |
| Hypothesis | Proposal of union |
| | Justification of the union |
| | Creation of the environment where the piece was placed as a whole |
| Virtual 3D representation | Virtual reconstruction |
| | Generation of QR codes (visualisation) |

# 3 Results and discussion

## 3.1 Pre-inspection phase

The pre-inspection consisted of a visit to the hosting site of the Visigothic Collection of the NMRA, to examine the two-sided reused piece (shield and columns) and the plaque (CE00548 and CE00470, respectively). The most significant characteristics that influenced the 3D digitization process were the dimensions and weight of the pieces. CE00470 is on display in the central nave of the church, while CE00548 is in one of the storage rooms, known as the "Sala de los Escudos" (shield room).

The possible disadvantages found when carrying out the 3D scanning of CE00548 were due to the difficulty in handling it. Due to the weight and dimensions of the piece, it was not possible to place it on the rotating plate of the scanner to complete the process. Therefore, the scans were conducted by moving the scanner around the piece, which made post-processing difficult, thus becoming semi-automatic. The main problem detected when inspecting the plaque (CE00470) was its disposition, since it was attached to a pedestal. This prevented the scanning of its rear part and made it impossible to use the turntable for scanning, as it could not be easily operated and moved, which slowed down the theoretical work. In addition, the calibration and data acquisition process for the structured light scanner was impaired, since the piece was in a room with non-adjustable lighting. Distortions may appear if the lumens are high on white and shiny surfaces within indoor lighting [53-55]. Some opaque featherboard rectangles of 50 x 70 cm were installed on the windows, which prevented the entry of lateral sunlight, in order to keep the main room with as little direct lighting as possible (20 lumens in the dark and 120 lumens in normal daylight). However, zenithal light was not prevented from entering, as the openings were more than five metres high.

## 3.2 Calibration

Calibration distinguishes between intrinsic (distortion, focal and optical centre) and extrinsic (orientation and translation) parameters [44]. A mathematical model allows taking into account geometric distortions and optical deviation [45]. There were problems in capturing the geometry of the pieces, since their surfaces reflect too much light. Therefore, and according to Rodrigues and Kormann [46], in order to fix this problem, a thin layer of opaque lacquer or powder was applied to the places that generate this type of issue.

Calibration consists of minimising the re-projection errors, i.e., the error among the places detected as markers in the acquired projection image, the location of these markers based on the phantom model and the current estimation of the image geometry [56]. Geometric calibration requires a checkerboard pattern (Figure 1). The procedure consists in taking photographs of a 300 x 500 mm chess board with a 15 x 21 cell square (18.85 mm side length) and coloured in green and pink to highlight the contrast between the cells. A minimum of 9 shots with different checkerboard angles must be taken, according to the Mephisto CX scanner manual (4ddynamics®), in order to reliably calibrate the scanner.

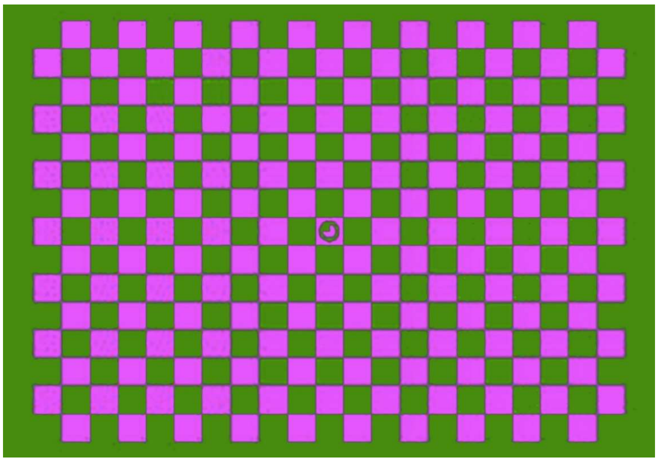


**Figure 1. Checkerboard pattern used for scanning with the Mephisto CX structured light scanner.**

## 3.3 Scanning the 2-sided reused piece (shield and columns) - (CE00548)

The 2-sided reused piece was the first to be scanned, which had to be conducted both on the surface of the shield and on the back, where the columns are. Figure 2 shows the shield, the first side to be scanned. It was placed on a wooden base to raise it 90 cm above the ground, placing it in a horizontal position to digitise the carved surface of the columns. Then, it was turned to digitise the frontal surface, which corresponded to the shield.

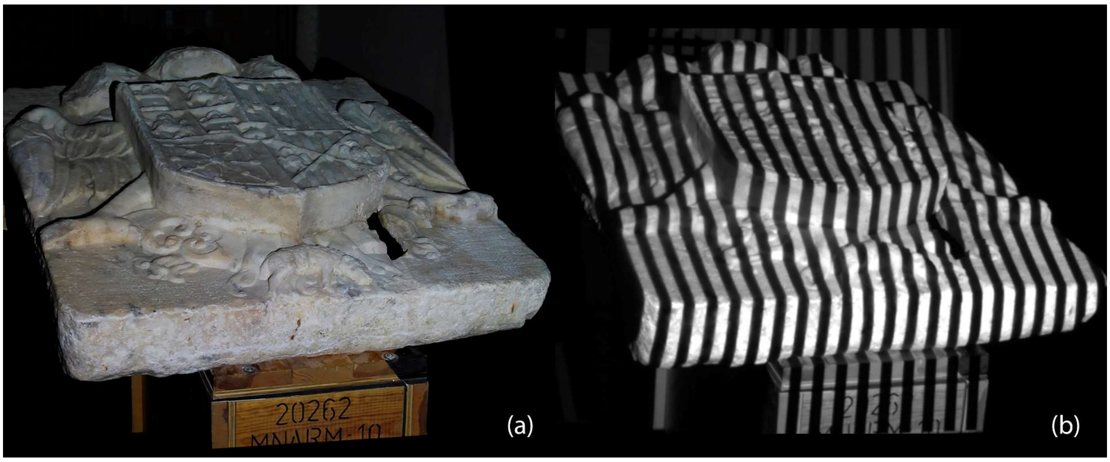



**Figure 2. Scan of the reused piece (shield side) using the structured light scanner in the Shield Room before (a) and during the scanning (b).**

The absence of the turntable made it impossible to automate the process. Therefore, control points on the piece itself were used to align the different scans, in order to overlap the scans [57]. To scan the carved surface of the columns, presented in Figure 3, images were captured from 17 positions around it, with the scanner at a height of 150 cm and at a distance of 0.9 m from the piece. To obtain some shots, especially in the central part of the piece, the tripod was raised to a height of 180 cm.

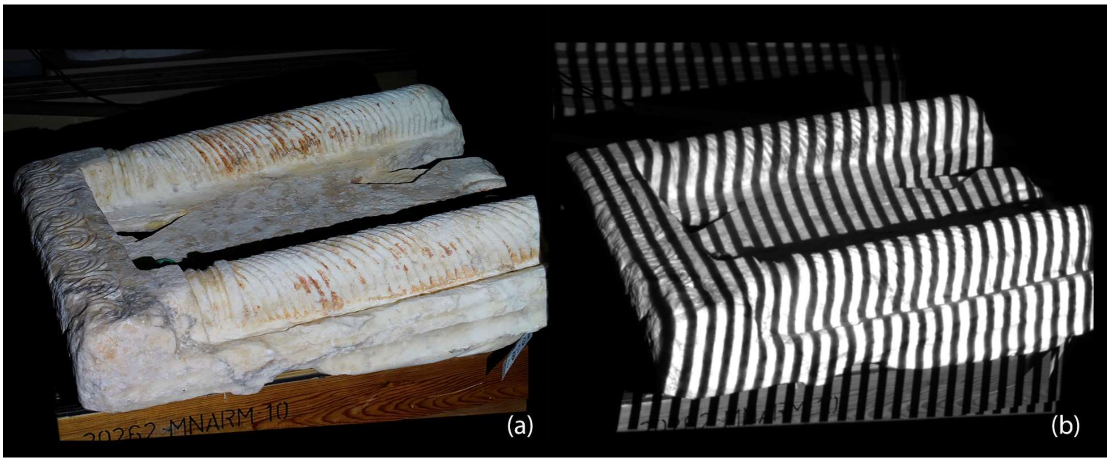



**Figure 3. Scan of the reused piece (column side) using the structured light scanner in the Shield Room before (a) and during the scanning (b).**

The computer connected to the scanner allowed visualising the results of the scans generated by each shot. This information generated a raw point cloud (xyzRGB). The raw information contained valid geometric data and other data that did not belong to the piece itself. Later, the unwanted data was removed to set up the clean database, which corresponded only to the geometry of the piece. This process was tedious and time-consuming [58]. The different images were combined to create a global model of the scanned area, using the common points of the piece as a reference, which were easily identifiable in both scans. The geometric distribution of the matching points is very significant in the final object [59]. Subsequently, the piece was rotated in order to scan the back side, which corresponds to the columns (Figure 3). The initial calibration conditions were not changed (distance: 0.9 m to the scanner). Images were captured from 19 positions, with a rotation of 20 sexagesimal degrees. The time between shots ranged from 0.2 to 0.5 s. In total, to scan the reused piece, both on the frontal side (shield) and on the back side (columns), images were captured from 36 positions an approximate data collection time of about 3 hours (including calibration and assembly). Table 2 shows the results of the point cloud that made up the raw database (xyzRGB), after discarding the parts of the capture that did not correspond to our work. Of all the scanned points, 77% were effectively obtained after the cleaning process carried out in situ.

**Table 2. Geometric database obtained in the form of a cloud of points (xyzRGB) collected from the different shots taken on both sides of the reused piece using the structured light scanner.**

| | PIECE 1 – COLUMNS SIDE | | | PIECE 1 – SHIELD SIDE | | |
|---|---|---|---|---|---|---|
| Capture | Total Gross Data (points) | Filtered Data (points) | Effectivenes s (%) | Total Gross Data (points) | Filtered Data (points) | Effectivenes s (%) |
| 1 | 356,892 | 280,571 | 78.6 | 600,256 | 434,662 | 72.4 |
| 2 | 35,037 | 291,539 | 82.8 | 598,487 | 440,928 | 73.7 |
| 3 | 646,890 | 549,778 | 85.0 | 707,666 | 605,994 | 85.6 |
| 4 | 652,935 | 484,302 | 74.2 | 686,494 | 626,414 | 91.2 |
| 5 | 684,761 | 497,580 | 72.7 | 730,458 | 592,907 | 81.2 |
| 6 | 723,445 | 575,066 | 79.5 | 730,458 | 593,053 | 81.2 |
| 7 | 648,371 | 490,579 | 75.7 | 659,198 | 482,944 | 73.3 |
| 8 | 651,487 | 487,078 | 74.8 | 538,667 | 332,992 | 61.8 |
| 9 | 658,818 | 463,719 | 70.4 | 724,250 | 550,185 | 76.0 |
| 10 | 599,207 | 440,059 | 73.4 | 589,584 | 513,785 | 87.1 |
| 11 | 613,307 | 488,629 | 79.7 | 582,002 | 504,453 | 86.7 |
| 12 | 665,221 | 540,795 | 81.3 | 756,740 | 638,642 | 84.4 |
| 13 | 634,421 | 496,684 | 783 | 765,057 | 661,873 | 86.5 |
| 14 | 544,996 | 371,526 | 68.2 | 728,947 | 648,196 | 88.9 |
| 15 | 714,233 | 556,281 | 77.9 | 647,651 | 440,028 | 67.9 |
| 16 | 725,491 | 615,802 | 84.9 | 655,134 | 477,826 | 72.9 |
| 17 | 725,331 | 534,328 | 73.7 | 567,120 | 422,945 | 74.6 |
| 18 | - | - | - | 551,246 | 455,159 | 82.6 |
| 19 | - | - | - | 603,132 | 573,416 | 95.1 |
| 20 | - | - | - | - | - | - |
| Total | 10,240,951 | 7,883,745 | 77.0 | 12,422,547 | 9,996,402 | 80.5 |

## 3.4 Scanning the plaque - (CE00470)

The scanner was recalibrated to scan the plaque (CE00470) and obtain acceptable values in the new working environment (Figure 4).

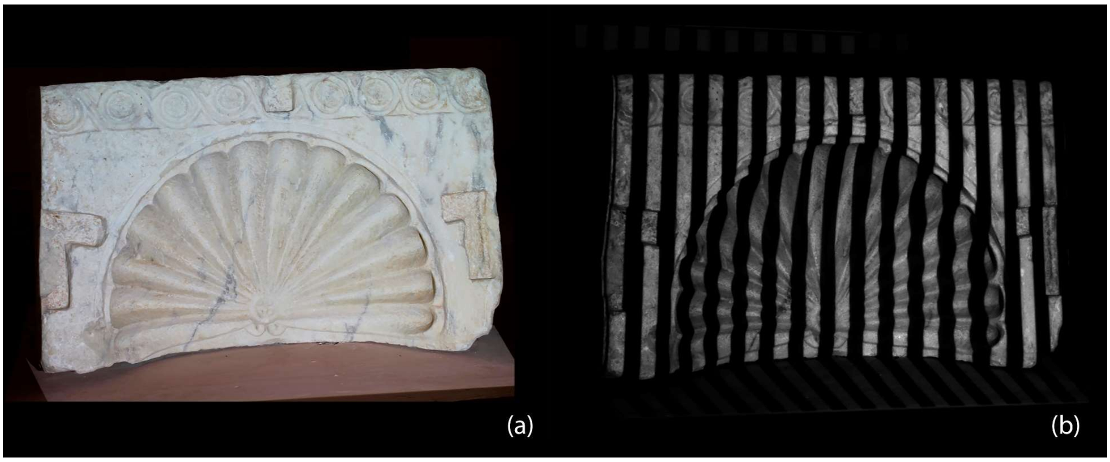



**Figure 4. Calibration of the structured light scanner in order to adapt it to the working conditions required by the plaque in the central aisle of Santa Clara.**

The scanner was placed around the plaque in ten different positions, due to the location of the piece, which was fixed on a pedestal next to the wall. Only the front and the two sides were documented, leaving the top and the back of the plaque undocumented. However, shots taken provided sufficient geometrical data to determine the volume of this piece (Table 3).

**Table 3. Geometric database obtained in the form of a cloud of points (xyzRGB) collected from the various shots taken from the plaque using the structured light scanner.**

| PIECE 2 – PLAQUE | | | |
|---|---|---|---|
| Capture | Total Gross Data (points) | Filtered Data (points) | Effectiveness (%) |
| 1 | 301,088 | 234,402 | 77.9 |
| 2 | 602,242 | 451,207 | 74.9 |
| 3 | 665,059 | 457,944 | 68.9 |
| 4 | 660,136 | 462,779 | 70.1 |
| 5 | 665,821 | 484,252 | 72.7 |
| 6 | 748,853 | 522,720 | 69.8 |
| 7 | 851,490 | 615,396 | 72.3 |
| 8 | 834,214 | 628,630 | 75.4 |
| 9 | 663,433 | 530,194 | 79.9 |
| 10 | 505,710 | 352,644 | 69.7 |
| 11 | - | - | - |
| 12 | - | - | - |
| 13 | - | - | - |
| 14 | - | - | - |

| | | | |
|---|---|---|---|
| 15 | - | - | - |
| 16 | - | - | - |
| 17 | - | - | - |
| 18 | - | - | - |
| 19 | - | - | - |
| 20 | - | - | - |
| Total | 6,498,046 | 4,740,168 | 72.9 |

Table 3 shows the total 6.498 million points (xyzRGB) that were obtained during the field work. Once the geometric points that did not belong to the piece (which could have been originated from other auxiliary elements) were discarded, the database was left with 4.740 million geometric points (xyzRGB). Therefore, the effectiveness of the capture was 72.9%. This process, although computerised, was carried out in the field with the scanner's software Mephisto 3.0 (4ddynamics®).

## 3.5 Office work

#### 3.5.1. Post-processing of the 2-sided reused piece (shield and columns) - CE00548

Mephisto Process 1.2 is the software used for the post-process (4ddynamics®). Starting from a complete database, the office work consisted in removing the auxiliary non-valid elements captured by the scanner to provide a clean and filtered geometric database. Then, an optimised database (xyzRGB) was searched and further simplified, eliminating the overlap caused by two consecutive images. The field-work data collection of piece 1 (shield and columns) was carried out in two different projects, one for each side. Table 4 shows the post-processing data for the 2-sided reused piece after unifying both results, originating a single database (xyzRGB), which generated a single three-dimensional model, after being optimised and meshed.

**Table 4. Post-process data of the 2-sided reused piece (shield and columns).**

| | POST-PROCESS | | |
|---|---|---|---|
| | Column surface | Shield Surface | Piece (1) Attached |
| TOTAL CLOUD (points) | 10,240,951 | 12,422,547 | 22,663,498 |
| MUFFLED CLOUD (points) | 7,883,745 | 9,996,402 | 17,880,147 |
| OPTIMISED CLOUD (points) | 5,557,993 | 4,244,243 | 9,759,913 |
| EFFECTIVENESS (%) | 70.5 | 42.5 | 54.6 |
| 3D MESH (triangles) | 11,115,870 | 8,485,840 | 19,519,246 |
| LENGTH (mm) | - | - | 663.97 |
| WIDTH (mm) | - | - | 790.57 |
| HEIGHT (mm) | - | - | 239.75 |
| SURFACE AREA ($cm^2$) | - | - | 15,618.78 |

| | | | |
|---|---|---|---|
| TOTAL REDUCTION IN VERTICES (%) | - | - | 21 |
| VERTICES | - | - | 4,786,543 |
| TOTAL MESH REDUCTION (%) | - | - | 52 |
| TRIANGLES | - | - | 10,127,230 |
| RESOLUTION (Dots x $cm^2$) | - | - | 306 |
| SIZE (Megabytes) | - | - | 461 |
| FORMAT (*.PLY) | - | - | (*.PLY) |

The three-dimensional model is a boundary representation, ready to be printed on any 3D printer. The raw database (xyzRGB) contained a total of 22,663,498 points, while the optimised database had 4,786,543 points, which led to a reduction of 79%, with a total remainder of 21% corresponding to vertices. The resolution of 306 points x $cm^2$ resulted in a three-dimensional model with a submillimetric separation between points (Figure 5). The resolution was optimal, since the separation between points was 0.327 mm, or 327 microns, for the 2-sided reused piece (shield and columns). As indicated by Torres-Martinez et al. [60], the power of the work station with which the data were collected, guarantees a reliable and rapid connection of the cloud and the resulting model. In our case, this was conducted with an Intel Core i5 processor and 8 GB of RAM. The work file used for both the point cloud and the 3D model was stored in a standard file as three-dimensional geometric information (*.PLY) (Polygon File Format).

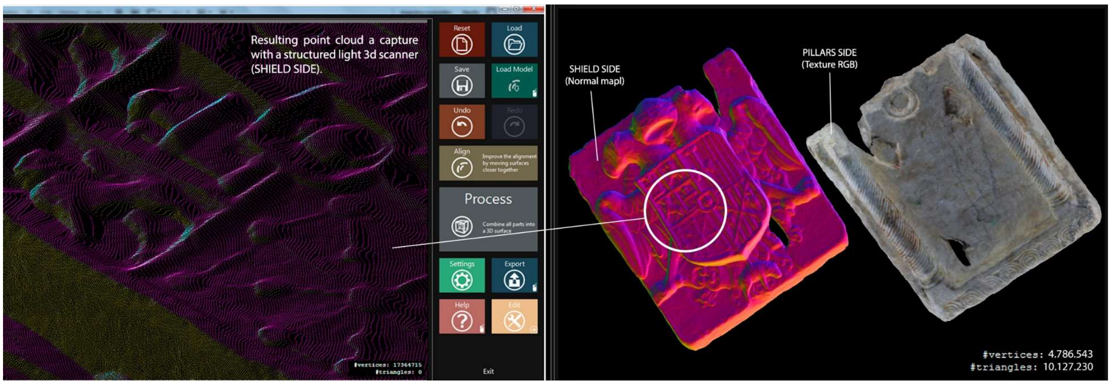



**Figure 5. View of the 2-sided reused piece (shield and columns) (CE00548) in Mephisto Process 1.2 (4ddynamics®).**

### 3.5.2. Post-processing applied to the plaque (CE00470)

The absence of geometric information in the rear and in the upper area made it difficult to obtain a solid, meshed and enclosed 3D model of the second piece, i.e., the plaque (Ref.CE00470). The total volume was obtained by extending both side surfaces, as these were scanned including the rear edge. The "close holes" tool was used to fill in the missing surface in both the upper and rear areas. Table 5 presents the results obtained in the post-processing for the plaque. In this piece, the data shows that there was a reduction of 76%, with a total of 24% corresponding to vertices.

**Table 5. Data from the post-processing of the plaques (CE00470).**

| POST-PROCESS | P2-PLAQUE |
|---|---|
| TOTAL CLOUD (points) | 10,240,951 |
| MUFFLED CLOUD (points) | 7,883,745 |
| OPTIMISED CLOUD (points) | 2,482,599 |
| EFFECTIVENESS (%) | 31 |
| 3D MESH (triangles) | 11,115,870 |
| LENGTH (mm) | 676.30 |
| WIDTH (mm) | 389.54 |
| HEIGHT (mm) | 175.58 |
| SURFACE AREA ($cm^2$) | 8,796.70 |
| VOLUME ($cm^3$) | 33,056.46 |
| TOTAL REDUCTION IN VERTICES (%) | 24 |
| VERTICES | 2,507,570 |
| TOTAL MESH REDUCTION (%) | 42 |
| 3D MESH (triangles) | 4,647,952 |
| RESOLUTION (Dots x $cm^2$) | 285 |
| SIZE (Megabytes) | 230 |
| FORMAT (*.PLY) | (*.PLY) |

The resolution obtained was 285 points x $cm^2$, which was the same as in the first piece. A 3D model with submillimetric resolution is shown in Figure 6.

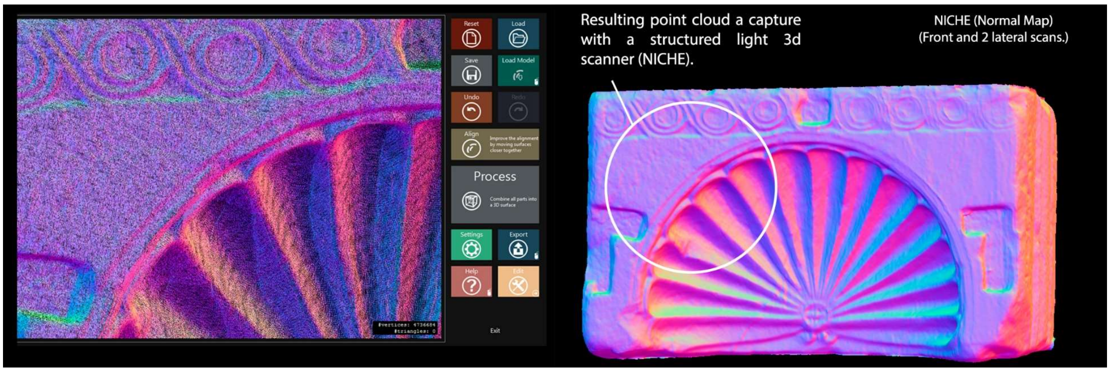



**Figure 6. Visigothic plaque with photographic textures.**

## 3.6 "x" Piece Configuration and Justification

After discussions with the curator of the NMRA, the following key points could be identified, which justified the relationship between the pieces under study, and served as a proposal for the configuration of the "x" piece. The upper decorative border and the lower border of the plaque were almost identical. The width of the two pieces was practically the same (66.39 cm and 67.63 cm). The difference, 1.24 cm, could correspond to the new carving of the piece. According to its origin, the plaque came from the Palace of the Duke de la Roca, where many archaeological pieces from the old Visigothic Cathedral were found, while the reused piece (shield and columns) came from the Hospital de los Reyes Católicos, located in the vicinity of the Cathedral. These two pieces seem to be designed to be embedded in a wall, thus the projection could be adapted and reduced to the minimum possible. On the one hand, the reused piece would have had its volume notably reduced in the modern re-cutting process, whereas, on the other hand, the shield was not thick enough to allow the pieces to fit properly.

Visigothic art is characterised by a certain laxity of form, which is why it would not be strictly necessary for the pieces to fit completely. Visigothic artists did not know how to solve the absorption of the flat part with the concave part, as we can see in examples where even these form a unitary part. They would try to estimate these results. The chapiters may or may not have a foundation. In any case, the ratio between height and width was not very wide. The succession of flat and concave surfaces without a concrete continuity is habitual in the design of Visigothic niches. Flat and concave shapes are involved in the piece, since it copies the classic shape of the niche. In addition, the flatness of the body may be due to the requirement of a flat surface for a correct adhesion of the jewels that could be embedded in the niches.

## 3.7 Modelling of the "x" piece

"x-piece" modelling is the 3D model proposed in the intermediate area between the two previously scanned pieces. Our objective was to model a piece that would connect geometrically and visually, both with the plaque (CE00470) and with the 2-sided reused piece (shield and columns) (CE00548). For the modelling, flat sections along the z-axis were applied to the mentioned 3D models (Figure 7).

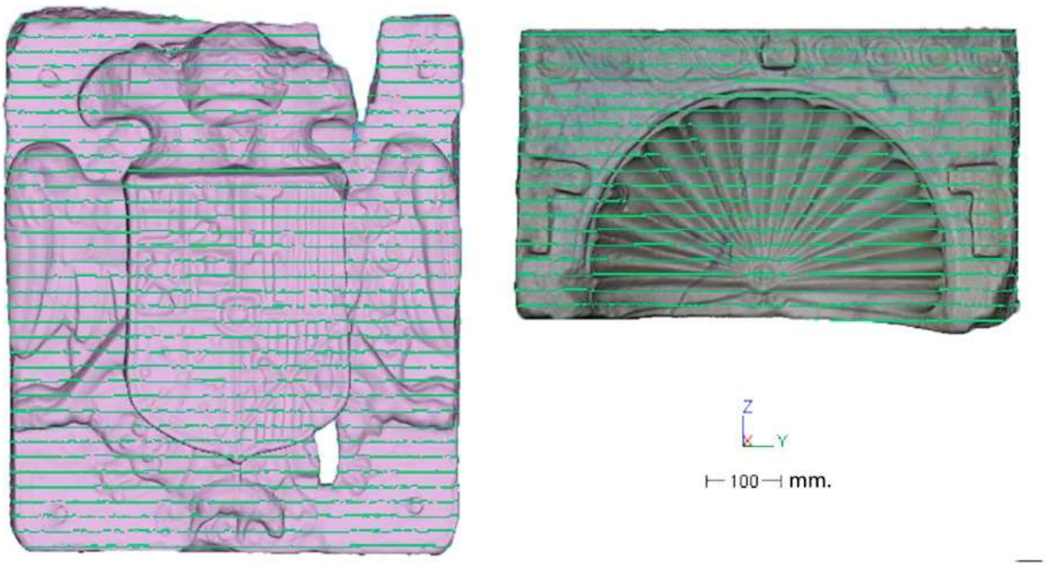



**Figure 7. Flat sections processed in 3DReshaper.**

The geometric bases of the design were established, with the help of these sections when modelling the "x" piece. A "sketch" was made to roughly represent the proposed connection between the two scanned pieces that made up the "x" piece (Figure 8). This piece was considered as an extension of the reused piece associated with the shield and the columns, which is, at the same time, the intermediate union with the plaque. Flat sections in both pieces were taken as a base (applied along the "z" axis every 20 mm) for a proper modelling, using the 3DReshaper software. Both columns were extruded using the Sketchup 2014 software, and finished off with chapiters of the period, resulting in a suitable geometry that constituted the definitive proposal of the "x" piece. This proposal of effective union was endorsed and approved by the curator of the NMRA, and follows the indications of authors such as Kedzierski et al. [59].

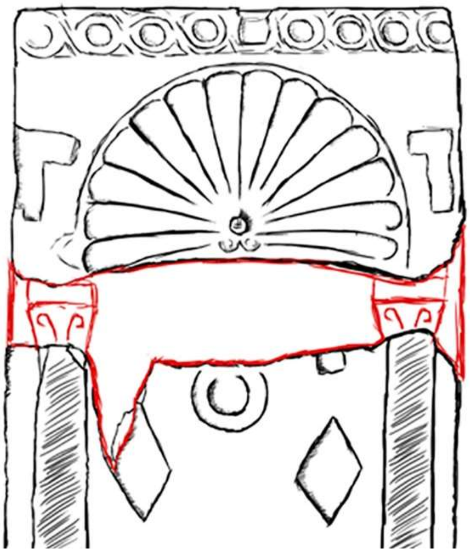


**Figure 8. Proposal of connection between the pieces of our project.**

The proposal for the overall model was made once the satisfactory model of the "x" piece was generated. This proposal would integrate the 3 resulting pieces: the two pieces scanned three-dimensionally and the "x" piece, modelled using the 3D design software Skechup 2018®.

Table 6 shows the data of the post-processing of the "x" piece and the 3D model of the whole composition. Regarding the "x" piece, the reduced number of vertices and surfaces, 646 and 1288 respectively, stand out, since they were modelled with simple geometry using Skechup 2018, occupying only 158 kb. The mesh of the "x" piece was subdivided using the Meshlab software in order to unify the geometrical characteristics of the 3 models. The Polygonal and Quad Mesh-subdivision Surface function was used, obtaining a mesh with 253 points/cm$^2$. These properties allowed the new piece to be smoothed and remodelled with submillimetric resolution. The 3D model has a total of 6,764,913 vertices and 14,083,966 surfaces, resulting in our case in a (*.PLY) (Polygon File Format) file of 1390 megabytes, and it corresponds to the data of the proposed union of the 3 pieces. This type of file (*.PLY) is very useful to preserve the model with submillimetric precision, although it is of little use when inserted in other rendering software in 3D environments. Therefore, from the same Meshlab v1.3.3 mesh editing software, a simplification and vertex reduction operation was performed. A new lighter model was generated (62.7 Mb), which guarantees a greater simplification regarding its operation.

**Table 6. Data of the combined post-process of the "x" piece.**

| POST-PROCESS IN OFFICE WORK |
| --- |

| | "X" PIECE (proposal) | PIECE 1+2+X (set of pieces) |
|---|---|---|
| TOTAL CLOUD (points) | - | - |
| MUFFLED CLOUD (points) | - | - |
| OPTIMISED CLOUD (points) | 646.00 | - |
| EFFECTIVENESS (%) | - | - |
| 3D MESH (triangles) | 1,288.00 | |
| LENGHT (mm) | 652.23 | 676.30 |
| WIDTH (mm) | 337.67 | 1,475.61 |
| HEIGHT (mm) | 222.91 | 290.13 |
| SURFACE AREA ($cm^2$) | 7,825.36 | 32,492.06 |
| VOLUME ($cm^3$) | 18,323.65 | 93,666.70 |
| TOTAL % REDUCTION IN VERTICES | - | - |
| VERTICES | 1,978,370 | 6,764,913 |
| TOTAL MESH REDUCTION (%) | - | - |
| TRIANGLES | 3,956,736 | 14,083,966 |
| RESOLUTION (Dots x $cm^2$) | 253 | 208 |
| SIZE (Megabytes) | 93 | 1,390 |
| FORMAT (*.PLY) | (*.PLY) | (*.PLY) |

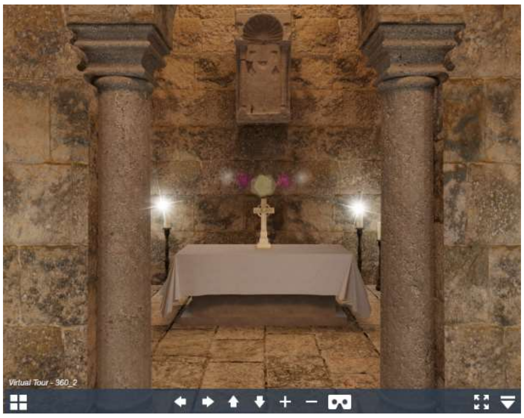
## 3.8 Dissemination of results

Cultural heritage digitalization is one of the main tools for its dissemination to improve the knowledge of the scientific community and the general public [61]. Online resources and interactive reconstructions stand out in the dissemination of the results, and were thus taken into account for the creation of the 3D model. In this study, two QR codes were generated to disseminate the results obtained in this investigation, where interpretation thrives in cultural heritage studies and enhances its understanding. Both cases offer a powerful query tool with three-dimensional geometric information. In addition, using these innovative codes favour the downloading of the files and allow the model to be 3D-printed.


https://skfb.ly/6UnVC

**Figure 9. QR code to access the interactive query of the proposed 3D model of the Visigothic niche.**

- The first QR code leads to the 3D model (real-time geometric data) obtained using a structured light scanner (Figure 9).
- The second QR code enables the 360-degree visualisation of the virtual reconstruction of the Visigothic niche. The head-mounted virtual glasses are a suitable device to be used to drive people into an immersive virtual visit (Figure 10). This tool helps to understand how Visigothic architecture may have been at the time.




http://www.digitalizados3d.es/nichovisigodomerida/tour.html

**Figure 10. QR code to access the virtual visit in a potential location of the Visigothic niche in an ecclesiastical context.**

The internal distribution of niches embedded in walls was taken into account for the insertion of the piece (Figure 11). The use of two pieces to generate a niche was a common formula in Visigothic art. Semper's theories about techniques and materials have been considered to better understand the use of separate blocks [62]. This is not an isolated phenomenon, as it can be found in other Visigothic examples, such as piece 188, referenced by Villalón [38]. Villalón referenced a loose, decontextualised niche that is currently in the Alcazaba of Mérida and was reused to place it in the Aljibe of the same fortified area. This research shows similarities with the niche embedded in the head of the shrine of Nuestra Señora de Portera in Garciaz, Cáceres.

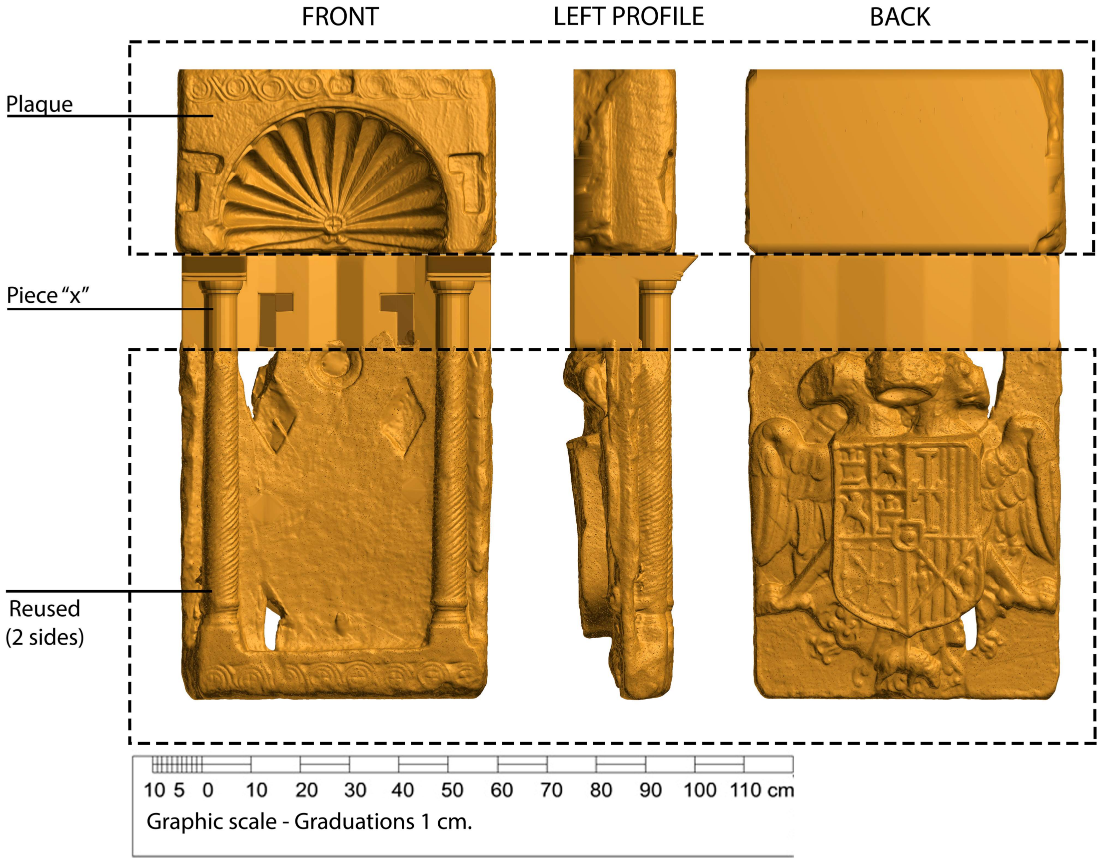



**Figure 11. Overall views (front, profile and rear) details in the central front area, the possible location of the jewels.**

Elements such as plate coatings, painted walls and curtains were incorporated to carry out the reliable 3D recreation. The incorporated horseshoe arch alludes to the Visigothic construction formulas. A textured finish was chosen to recreate the walls of the period, as well as a sand-textured finish for the floor. The real purpose was to study the relationship between the two pieces and the architectural structure. Figure 12 presents the final render image in the proposed environment.

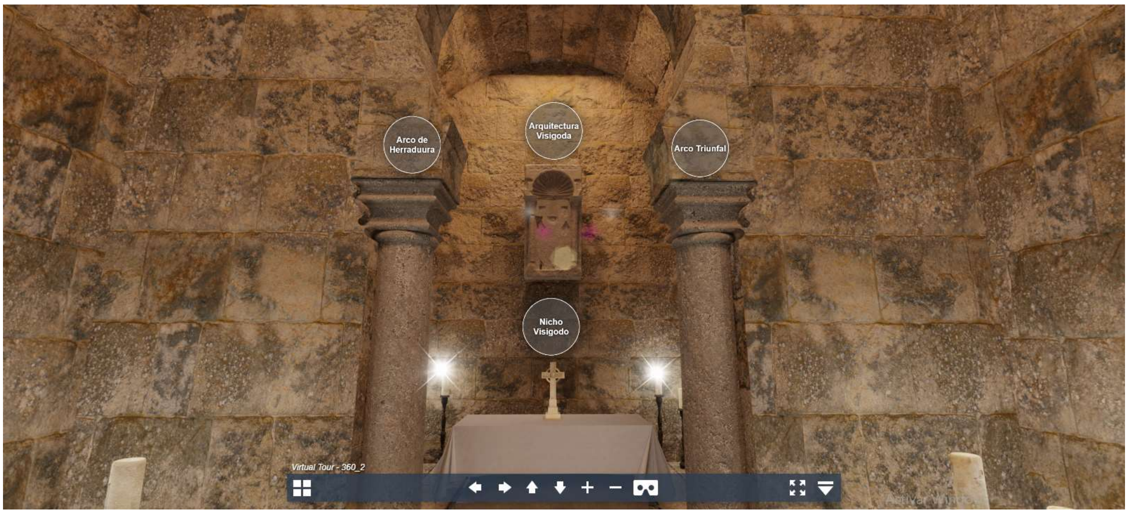



**Figure 12. Rendered image of the final result of the piece and its environment.**

## 4 Conclusions

From a theoretical point of view, the impact of the phenomenon of reused pieces in the field of art and architecture was verified, adding value to both diverse methodologies of study and examples. The knowledge of the state in which the level of graphic representation was found through an exhaustive analysis of the state of the art of the Visigothic archaeology of Merida.From the practical point of view, both the 2-sided reused piece (shield and columns) and the plaque were geometrically documented using a structured light scanner. This technique captured the 3D geometry of the study pieces with micrometric resolution. The virtual editing and manipulation of the resulting 3D models, using modelling programmes, allowed creating an intermediate piece called "x", which served as a link between the two pieces (the plaque and the 2-sided piece). After numerous verifications, both on a theoretical and practical level, this proposal links the pieces of our study: the CE00470 plaque and the CE00548 shield-and-columns, constituted, together with the aforementioned "x" piece, a Visigothic niche. The virtualisation of the 3D scanned pieces made it possible to formulate a proposal with high scientific accuracy. This will facilitate future research proposals, as well as their applicability in future projects within the scientific community.

Finally, a 3D virtual environment was recreated to locate the resulting Visigothic niche, with the aim of promoting the dissemination of the results of this investigation. The methodology implemented with decontextualised heritage pieces was very useful when a physical reconstruction was not feasible. This research provides archeologists, architects and restorers with innovative resources to visualise the 3D model of the Visigothic niche in an interactive way, at real time from any available device, through QR codes.

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