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Comparative Analysis Between the Main 3D Scanning Techniques: Photogrammetry, Terrestrial Laser Scanner, and Structured Light Scanner in Religious Imagery: The Case of The Holy Christ of the Blood

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In recent years, three-dimensional (3D) scanning has become the main tool for recording, documenting, and preserving cultural heritage in the long term. It has become the “document” most in demand today by historians, curators, and art restorers to carry out their work based on a “digital twin,” that is, a totally reliable and accurate model of the object in question. Thanks to 3D scanning, we can preserve reliable models in digital format of the real state of our heritage, some of which are currently destroyed. The first step is to digitize our heritage with the highest possible quality and precision. To do this, it will be necessary to identify the most appropriate technique. In this article, we will show some of the main digitization techniques currently used in sculpture heritage and the workflows associated with them to obtain high-quality models. Finally, a complete comparative analysis will be made to show their main advantages and disadvantages.

CCS Concepts: • **Hardware** → *Emerging technologies*; • **Computing methodologies** → *Computer graphics*; • **Applied computing** → *Operations research*;

Additional Key Words and Phrases: Digital photogrammetry, terrestrial laser scanner, structured light scanner, cultural heritage, 3D scanning, 3D models, workflow, dimensional control, spectrophotometer, colorimetry

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1 INTRODUCTION

At present, there is no definitive or foolproof technique that allows the three-dimensional (3D) scanning of a wide variety of physical objects regardless of their characteristics. There are many variables that condition

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the success of this process: the location of the object' its size, shape, color, level of detail, or resolution; and the characteristics of the environment in which it is located (lighting, accessibility, etc.). The most widely used 3D scanning techniques at present are digital photogrammetry, laser scanner (terrestrial), and structured light scanner. In this article, we will study the workflows of each, execution times, results, and more applied to the particular case of a polychrome wood sculpture, that of the *Holy Christ of the Blood* by Nicolás de Bussy (1693).

Through this comparison, we intend to identify the strengths and weaknesses of each technology according to the characteristics of the object to be digitized and its environment under the premise of ensuring maximum efficiency and quality of the digital information extracted (geometry and texture or color) for future applications, such as research, partial or total reproduction of replicas for conservation purposes, exhibition, digital display, and so on.

2 STATE OF THE ART

Advances in technology are continuous—practically every day, new active and passive sensors emerge for the data capture of objects, new means of acquisition, new processing algorithms, more powerful processing devices, and software better adapted to organic and complex geometries. These allow data capture and processing to achieve some standardization through similar workflows.

Technologies are changing many aspects of our lives—the way we interact, learn, and work. There are already numerous articles on the operation of these technologies through case studies. However, as technology evolves, new comparative studies of different 3D scanning techniques are needed, studying both their surface geometry and other issues, such as the scale and fidelity of the captured color.

The techniques that prevail over the others for 3D digitization and documentation are the structured light scanner, laser scanner, and short-range photogrammetry due to the combination of characteristics that enable their use: accessible technology, lower acquisition costs, faster processing, ease of use for inexperienced users, articles describing their use, and high-precision results, among others.

Metric evaluations of heritage assets have been carried out by Remondino et al. [1], by Nabil and Saleh [2] of SfM software, by Evgenikou and Georgopoulos [3], and the use of Morena's structured light hand scanner [4].

Other authors have also focused on conducting studies focusing on white light scanners and photogrammetry—specifically, Katz and Friess [5] and Evin et al. [6] compared 3D models created by photogrammetry and a light scanner. Some also include time values (for data acquisition and processing) to evaluate the efficiency of the methods. In contrast, Girelli et al. [7] describe the integration of techniques based on 3D images and ranges, comparing the final scale and describing the data processing operations related to the digitization of objects.

In summary, previous authors suggest that photogrammetry appears to be a reliable method to obtain high-quality 3D surface models (as well as structured light ones), while structured light and laser 3D scanners appear to be more efficient. However, the meshes created in laser scanners usually do not seem to present the same quality as those created by photogrammetry.

Despite frequent evaluations of the aforementioned 3D digitizing techniques found in the literature, they quickly become obsolete due to rapid technological advances. The present study seeks to show the workflows comparing the most commonly used 3D scanning techniques in addition to evaluating certain parameters such as the geometric level of mesh processing, the scale obtained from the object, and the colorimetric quality.

3 SCULPTURAL ANALYSIS OF THE SIZE OF THE HOLY CHRIST OF THE BLOOD

The *Holy Christ of the Blood* is one of the most transcendental sculptural images in the history of Baroque art in Spain. Its dimensions are $140 \times 140 \times 56$ cm. It was made by Nicolás de Bussy (Strasbourg, ca. 1640–Valencia, 1706), an artist who worked mainly in the old kingdoms of Valencia and Murcia, for the Archconfraternity of the Precious Blood of Murcia in 1693 [8–12]. It was for this penitential brotherhood that he produced most of his documented work. Until recently, not much information was known about his life, especially regarding

his arrival in Spain. His first biographer, the great treatise writer and painter Antonio Palomino (1655–1726), considered him to be a member of a select group that arrived at the court of Charles II with the military man and politician Juan José de Austria (1629–1679), which has not yet been proven. Thanks to the latest studies, his works have been documented in Valencia, Elche, Alicante, the Real Sitio de Aranjuez, as well as in Murcia (most of the southeast of Spain).

The *Holy Christ of the Blood* is a masterpiece because of its excellent workmanship and deep iconographic significance. It is made of polychrome wood, a technique developed especially in the Catholic world, distinctively in Spain during the Modern Age, where the imagery of Holy Week reached a high degree of perfection in the Baroque period. Its realistic character and persuasive mechanisms emotionally moved the spectators, making them participants in the sacred dramatization of the Passion of Christ. Elements such as the wig of natural hair, the crown of thorns, or the blood that emanates from the side added greater realism. From an iconographic point of view, it constitutes a unicum since it represents an ancient type of medieval origin, “Christ in the Mystical Winepress,” which is unusual in the Spanish Holy Week. It represents Christ nailed by the short arm of the cross, which he carries on his shoulders while he seems to walk, although he actually steps on the wine press. He was accompanied by five child angels collecting the blood/wine that came out of his sides, a symbol of redemption, of which he now carries only one.

From a stylistic point of view, the sculpture is characterized by its realism, its perfect anatomical study, and its great drama. The children who accompanied him, with their expressions of compassion and tenderness, gave a greater effect to the whole, typical of baroque theatricality, which the great Strasbourg sculptor knew how to handle with total mastery. From the technical point of view, it is worth noting how Bussy used cypress wood, a durable material that is highly resistant to attacks by xylophages, and how the polychrome was made with pigments agglutinated with drying oils [13]. The polychrome system has been well studied by Fernández Labaña [14], especially in the carnations, as it omitted the traditional layer of plaster or rigging, which meant that it had to be used thoroughly to leave the wood well finished, with an exquisite treatment, applying an orange layer composed of minimum pigment agglutinated in oil [14]. This is a peculiar way of working that distinguishes him from other sculptors working in Murcia in the Modern Age and that is very useful to confirm or reject undocumented authorships of his works.

The restorations that have been carried out in the work have allowed us to have a better knowledge of the sculptural process. Unfortunately, the *Holy Christ of the Blood* was practically destroyed in the Spanish Civil War (1936–1939), “with great loss of support and cracks” [13], especially one that ran along the chest and tore part of the calf and ankle of the right leg and that, at present, is still a particularly sensitive and problematic area despite the restorations. The body was fragmented into 30 parts, which were collected by the artist Clemente Cantos, recomposed without the head (recovered later) by the sculptor Juan González in October 1939, and identified by the Murcia Artistic Treasure Board (Figure 1). The head was charred and the nose had practically disappeared. However, the sculptor José Sánchez Lozano took charge of the total restoration of the carving, with the repolymerization of the head and adaptation to the body, work which was completed in 1941. Only two children were found, who were also operated on at that time.

Both sculptors González Moreno and, fundamentally, Sánchez Lozano, contributed to the important recovery of this unique image, with the re-polychrome of the devastated areas and the reintegration of the lagoons with oil. Subsequently, small one-off interventions were carried out until 1991, when it was restored in the Museum of Fine Arts in Murcia, due to the opening of cracks and its general state of deterioration. The problem of the crack in the leg was then corrected with a stainless steel rod to absorb the movements that originated in the work described in [13]. New wooden spikes were included in the left arm, reintegrating all of the gaps with the elimination of repaints while respecting the repaints of the face since, due to the fire, the original polychrome had not been preserved.

The most transcendental intervention was carried out by the Restoration Center of the Region of Murcia between 2003 and 2004 (Figure 2) after the alterations of the reintegration and the opening of cracks again [13,

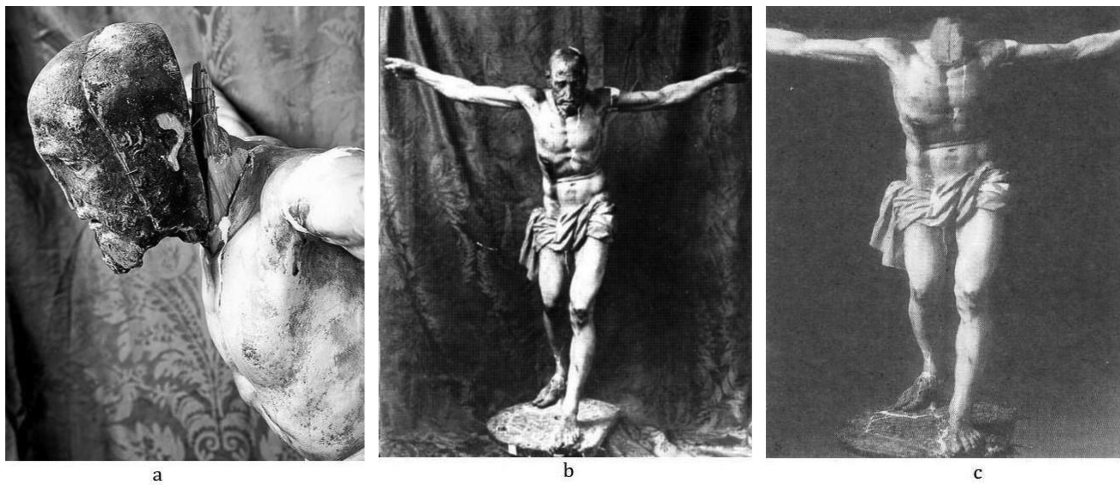


Fig. 1. (a) and (b) Images of the destruction that took place in 1936 on the carving of Christ [15]. (c) Photo of the Cristo de la Sangre before incorporating the head—Cristobal Belda (1940) [13].

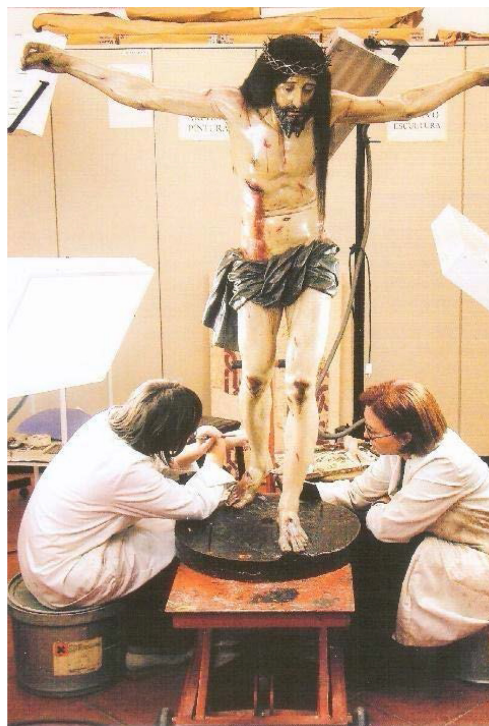


Fig. 2. Restoration of the *Cristo de la Sangre* in 2004 [13].

16]. Techniques such as ultraviolet light to study the alteration of the repainting and endoscopic exploration to analyze the internal state of the wood and the sculptor's working techniques confirmed that González Moreno joined the fragments and stuccoed joints and cracks, and that Sánchez Lozano restored the burnt head, closed the box of the body of the sculpture, and reintegrated the polychrome of the image. Other techniques—such as stratigraphic and analytical studies in order to determine the materials and pigments used—corroborated Bussy's procedures and determined which was the original polychrome. As noted earlier, Bussy used a single layer of original paint, mostly flesh paint, over which was superimposed the one simulating blood, “from a thick layer of red lacquer, as a glaze, over a thin opaque red background, applied over the flesh” [16]. The pigments used show how some would be used later in possible interventions before the middle of the 19th century and after this date. In the opaque and transparent whites were found gypsum, albayalde, calcium carbonate, barium white, and zinc white; in the black, charcoal was found. In the red colors was found the earth rich in iron oxide, vermilion, red lacquer, and shaded earths. There are also blue, orange and brown colors [16].

X-rays taken at the Ibermutuamur Clinic helped to distinguish new nails from old ones and facilitated the study of the original joints and forging nails, the types of wood, and the clarification of the joints. Mainly, it shed light on the intervention of Sánchez Lozano in the head. This consisted of additions to the nose and bearded tufts as well as their total repolymerization [13]. After all of these previous studies, we proceeded to its intervention, betting for an illusionist reintegration, being a sculpture devotion and public cult, differentiated with the techniques of *regattino* and *puntello*. Through a color sitting, deep-cleaning tasting, and physical-chemical cleaning—with the elimination of oxidized varnishes, dirt, and repaints—the removal of old stuccos was carried out and replaced by new ones, with the chromatic reintegration of gaps and the application of protective varnishes. A whole intervention was performed that allowed not only the improvement of image conservation but also the study of Nicolás de Bussy's sculptural techniques.

4 3D DIGITIZATION TECHNIQUES FOR HERITAGE PRESERVATION AND WORKFLOW DESCRIPTION

4.1 Main 3D Digitization Techniques for Heritage Preservation

There is a very wide variety of techniques for 3D scanning. In some, it is necessary to have previous technical knowledge of scanning and 3D processing. Others are accessible to more basic users. Generally, all digitization techniques have certain advantages and disadvantages depending on the object to be digitized [17]. The main challenge in obtaining a 3D technology of the highest geometric quality and resolution lies first in identifying the most appropriate model and second the application of the most suitable method or workflow. In this article, we will show the main advantages and disadvantages plus similarities and differences of the most commonly used digitization techniques in sculptural heritage (Figure 3).

All of the techniques to be considered by our studio are “non-contact” techniques, because they do not need to physically touch the object. Digital photogrammetry is a passive technique based on the Structure from Motion (SfM) system, while the terrestrial laser scanner and the structured light scanner are Active Optical Reflection Triangulation techniques (Figure 4).

For photogrammetry digitization, the Sony Alpha 7R reflex camera with a Sony SEL50F1.8 fixed focal length 50-mm lens was used. The terrestrial laser scanner used was the Faro Focus S150 and the Artec Eva structured light scanner. The choice of these three 3D digitization techniques was made due to their relevancy to this study and our experience in their use.

Digital photogrammetry consists of a technology based on the detection and homologation of significant and common points in a quantity of images to obtain 3D objects. We mainly use it to document small objects without the need to obtain high accuracy or to quickly document heritage objects that may be in places difficult to access, where the use of 3D scanners is very complicated. Digital photogrammetry has been shown to provide accurate data. However, it presents significant problems in low-light environments, dark surfaces, or reflective objects

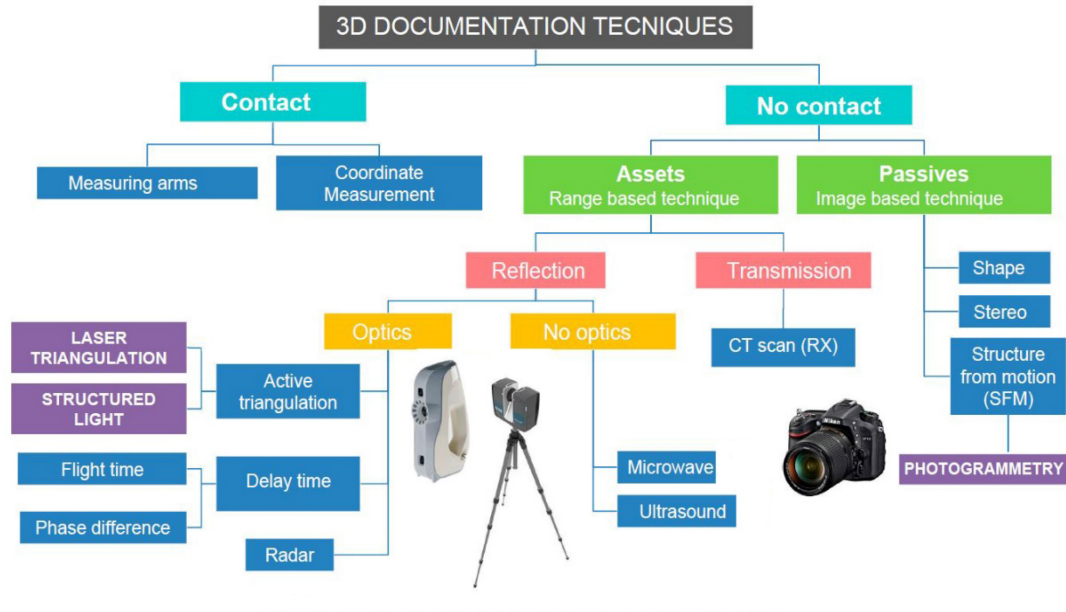


Fig. 3. Diagram of the main 3D scanning techniques.

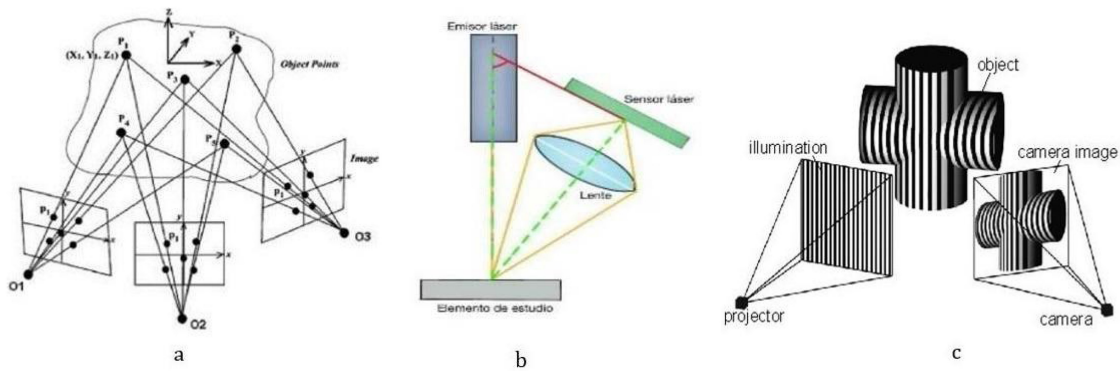


Fig. 4. Theoretical explanation of 3D scanning techniques: (a) photogrammetry, (b) laser scanner, (c) structured light scanner.

[18]. It is a method with which models can be obtained relatively quickly but with little precision especially in scale if visual metric references such as scale bars are not used. In addition, in general, it is necessary to make many images or photographic sessions in an environment of very controlled and constant luminosity. The description of this technique and its workflow is provided in [19]. The terrestrial laser scanner is a long- or medium-range scanner that uses active triangulation technology, in which the emitted laser bounces off the surface of the object and returns the laser pulse to the scanner. A calculation method that combines the distance between the scanner and the object, the speed of light and the time of flight of the laser pulse will result in the point cloud of the object. This is a scanner suitable for obtaining precise and high-resolution models of large surfaces or objects [20]. However, as we will see throughout the article, it is unsuitable for objects of medium to small size or of significant geometric complexity.

The structured light scanner also uses active triangulation technology. However, unlike the terrestrial laser scanner, the structured light works by projecting a pattern of white or blue light onto the object instead of a laser pulse. The light pattern (usually a series of stripes or dot matrix) is projected onto the object using a projector, while the scanner's cameras observe the light pattern and calculate the distance to each point in the field of view. The main advantages of this technology are speed, accuracy, and high resolution. It is currently the most suitable technique for digitizing medium to small heritage objects with a high level of detail and geometric composition. In addition, it obtains high quality in the capture and replication of the object's real textures and colors [21].

It should be noted that digital photogrammetry and laser scanner techniques are long-range capture techniques, while the structured light scanner is a short-range scanner.

4.2 Description of the Workflow for 3D Scanning by Terrestrial Laser Scanner and Structured Light Scanner

We will start with a description of the workflows of the terrestrial laser scanner and structured light scanner techniques since photogrammetry techniques performed on the carving of the *Holy Christ of the Blood* is already described in another article [19].

The digitization workflow of these two techniques, as was proved with photogrammetry, is mainly divided in two well-differentiated phases—data taking and processing of the data—although with small differences that will be described next.

It is considered necessary to include the following information about the process of photogrammetry to introduce this method also for comparison although the process is described in [19].

As mentioned earlier, a Sony Alpha 7R camera was used with a Sony SEL50F 1.8 lens with a 50-mm fixed focal length and ISO 100. The resolution chosen was the maximum of the camera's sensor, 36.4 Megapixels in RAW format, the pitch being 4.88 μm pixel size. For the lighting of the photographic session, halogen and LED bulbs were used, adjusted to 5500K of temperature (cold light) to preserve the colors of the polychrome, and to which diffusers were attached to try to minimize glare. By adjusting the lighting in this way, it was decided not to use a white balance using a color chart. The images were masked, that is, the background was eliminated in each photograph, in order to keep only the information that interests us. During the image-taking process, chroma key type backgrounds were used due to their high contrast facilitating this discrimination operation. Most of the images were captured on a tripod except for the images belonging to the upper areas—head, hands, and so on. Scale bars were used to adjust the scale deviation. The software chosen for processing was Agisoft Photoscan Professional.

The comparison of the 3 techniques will be carried out studying some technical aspects, level of detail, surface noise, processing time, dimensions, and more, as seen in Table 1.

4.2.1 Workflow Description for 3D Scanning with the Artec Eva Structured Light Scanner.

4.2.1.1 Analysis of the Environment for the Acquisition of Digital Information. As happened with the digitalization of the *Holy Christ of the Blood* by digital photogrammetry, it is necessary to adapt the working environment where the Christ is located because it is permanently exposed to the congregation in the Chapel of the Bell attached to the main building of the Church of Carmen in Murcia and the Museum of the Archconfraternity of the Precious Blood (Murcia, Spain).

Therefore, it is necessary to lower the carving of the Christ from its altar to the floor in order to scan the whole surface of the object in a more comfortable and adequate way. The operating distance of the Artec Eva structured light scanner is between 0.4 and 1 m. Therefore, it will be necessary to have at least one meter of free space around the object.

As far as the lighting conditions of the environment are concerned, this scanner does not need artificial light support as it has a built-in flash, which produces a constant and uniform light source, illuminating the object along its surface and obtaining a high-quality texture and color similarity.

Table 1. Comparison of the 3D Scanning Techniques

METHODOLOGY	PHOTOGRAMMETRY	STRUCTURED LIGHT SCANNER	LASER SCANNER
MODEL	Sony Alpha 7R	Eva Artec 3D	Faro S150
SOFTWARE	Agisoft Photoscan	Artec Studio 14	Scene
APPLICATION			
ENVIRONMENTAL ADAPTATION			
Operating distance	Variable	0.4–1 m	1.5–2 m
Lighting control	Yes	No	No (yes for texture)
Markers	No (advised)	No	No (advised)
Scale bars	Yes	No	No
DATA ACQUISITION			
Data collection	Manual	Manual	Automatic
Capture method	Photographic	Geometry + Texture	Geometry + Texture
Scan speed	—	11 FPS	15 minutes/scan
Number of positions	1137 photographs	37 scans	14 scans
Capture time	16 hours (4 sessions) (4 hours/session)	1 hour	4 hours
DATA PROCESSING			
Hardware	CPU: Intel Core i7 8Gen 3, 2GHz RAM: 16 GB Graphic card: GeForce RTX2080 8 GB SSD 500 GB	CPU: AMD Ryzen 9 3900 × 3.8 GHz BOX RAM: 32 GB (Corsair Vengeance LPX DDR4 3200 PC4-25600 32 GB 2 × 16 GB CL16) Graphic card: RTX 2060 (Gigabyte GeForce Super Windforce OC 8 GB GDDR6) 1 TB SSD y 2 TB HDD	CPU: AMD Ryzen 9 3900 × 3.8 GHz BOX RAM: 32 GB (Corsair Vengeance LPX DDR4 3200 PC4-25600 32 GB 2 × 16 GB CL16) Graphic card: RTX 2060 (Gigabyte GeForce Super Windforce OC 8 GB GDDR6) 1 TB SSD y 2 TB HDD
Processing time (registration, gaps-filling)	3883 minutes (2 days, 16 hours, 33 minutes)	2 hours	30 minutes
RESULTS			
Processing time (registration, gap-filling)	4843 minutes (3 days, 8 hours, 33 minutes)	180 minutes	270 minutes (4 hours, 48 minutes)
Noise	Low (masks)	Medium	High
3D mesh quality	Medium	High	Low
Texture	Extra high	Extra high	Low
Number of points	49.845.771	85.771.521	1.865.599
Number of polygons	9.969.242	10.000.000	584.308
Resolution	-	0.3 mm	3 mm/10 m
Volume	0.068	0.066	0.069

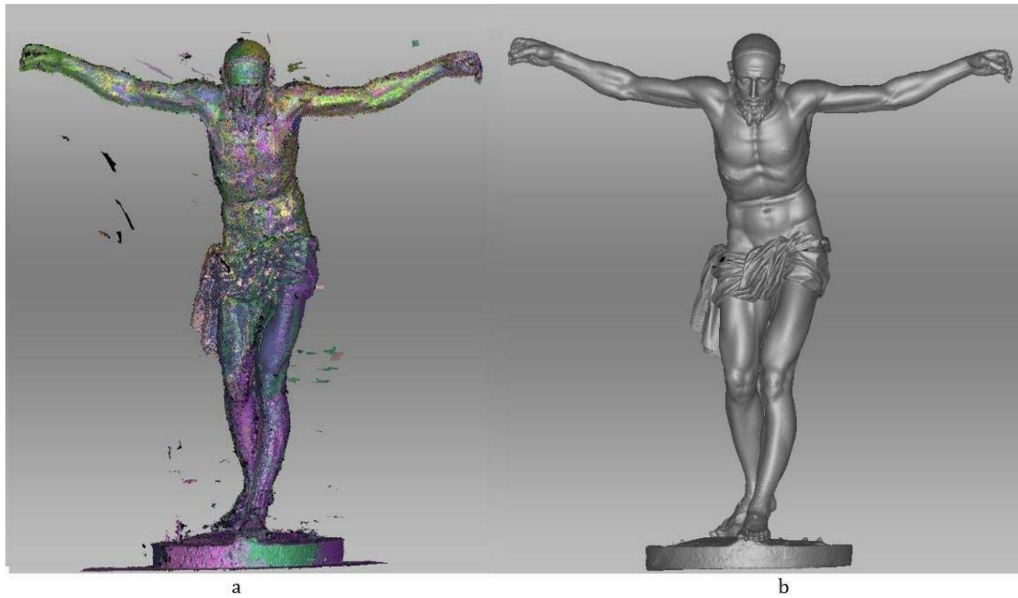


Fig. 5. (a) Point cloud after alignment. (b) 3D mesh obtained after processing with the Artec Eva structured light scanner.

4.2.1.2 Data Capture. Before starting the manual scanning of the object, it is worth mentioning that the Artec Eva structured light scanner does not need markers or scale bars, as this scanner captures the object in real scale with great precision. It has a scanning area of height $\times$ width in the near range of 214 mm $\times$ 148 mm and in the far range of 536 mm $\times$ 371 mm.

Starting with the description of the working process of scanning with the Artec Eva structured light scanner, we will use the following technical parameters in the Artec Studio 14 scanner software:

- Scanning method: Geometry + Texture
- Scanning speed: 11 FPS
- Depth of field: Near, 400 mm; far, 1000 mm
- Flash: On
- Texture: Adjusting the brightness of the texture manually (user)
- Real-time merging

We will start by using the scanner preview to adjust these parameters and the brightness of the texture color, which can be seen and adjusted only in this mode. Then, we will proceed to scan, observing in real time the parts that are being captured since we have chosen the option of real-time fusion. A total of 37 scans were made in 1 hour.

4.2.1.3 Data Processing. The processing of the data acquired by the Artec Eva structured light scanner will also be carried out in the Artec Studio 14 software, and will involve a series of actions described here:

- Alignment of the scans: It is necessary to align the 37 scans with each other. For this purpose, the alignment method has been chosen from 3 points. Figure 5(a) shows the result of the alignments made in the digitalization of the *Holy Christ of the Blood*. Each color of the point cloud corresponds to a different scanning session.

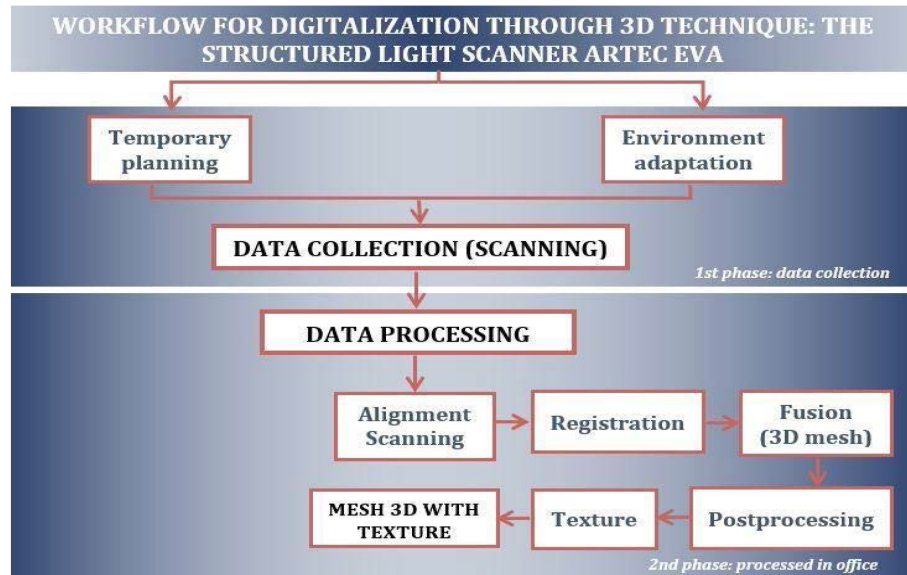


Fig. 6. Workflow diagram—Artec Eva structured light scanner.

- Registration: First, a fine registration has been made with the algorithm of geometry and texture and, later, a global registration with the algorithm: geometry and texture. This algorithm selects geometrical points from each scan frame and compares them to each other, obtaining information about the relative positions of each point pair. In this way, it corrects possible errors or failures of the previous alignment, optimizing the position of all of the frames in a global coordinate system.
- Removal of noise and other data: This process allows us to remove the base (ground) or other outliers or noise that are not attached to the main surface.
- Merging: This consists of the creation of the 3D mesh, using the smooth merging mode, with 0.3-mm resolution. We obtain a mesh of 51,163,728 million polygons (Figure 5(b)).
- Post-processing: Tools are used to repair and close the mesh (small object filter, hole filling, mesh simplification, isotropic re-meshing, etc.). It should be noted that a model with non-significant holes in relation to the object's dimension was obtained.
- Color layer: Creation of the texture from selected scans in .jpg format and size 4096×4096 with a resolution of 120 pixels per inch (dpi).

Figure 6 shows the summary diagram of the workflow established with the Artec Eva structured light scanner technique.

4.2.2 Workflow Description for 3D Scanning with the Faro Focus S150 Laser Scanner.

4.2.2.1 Analysis of the Environment for the Acquisition of Digital Information. In the case of the laser scanner, as with the other techniques, it is necessary to adapt the working environment. It will be necessary to lower the Christ from its altar to the floor in order to scan the entire surface of the object properly. The operating distance of the Faro Focus S150 laser scanner is 0.5 m. However, to increase the accuracy of the 3D model and capture the full scale, spherical markers are used on the perimeter. This circumstance and the need to place the scanner on a tripod to perform the capture from various heights increase that distance by at least 1.5 to 2 m around the object. As for the lighting conditions, although this scanner does not need any kind of illumination to capture

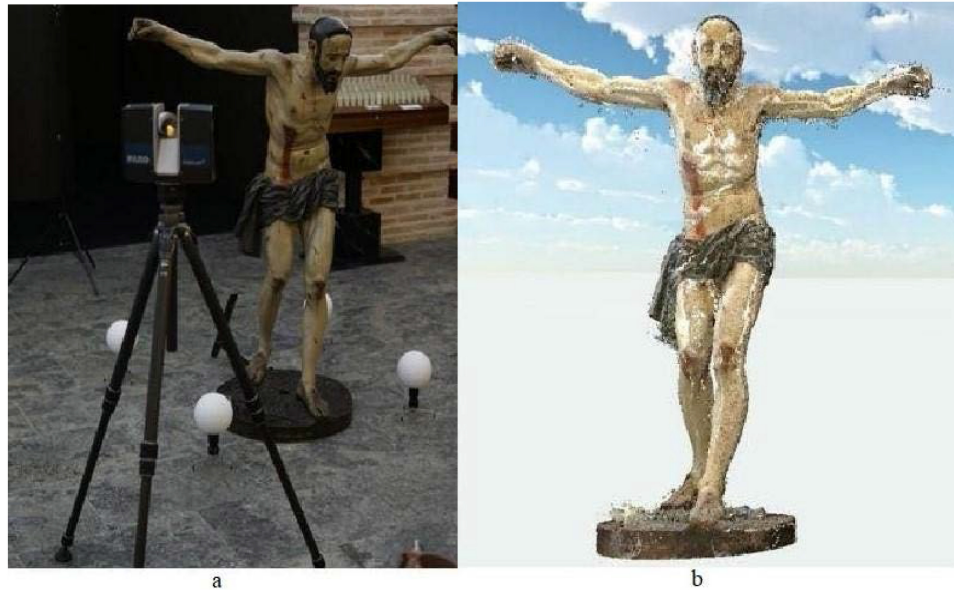


Fig. 7. (a) Data capture. (b) Point cloud obtained from the Faro Focus S150 laser scanner.

the geometry of the object, it does need uniform artificial lighting along the entire surface of the object for the correct capture of the texture.

4.2.2.2 Data Capture. As can be seen in Figure 7(a), one begins by placing 4 spherical markers around the Christ in a position close to the object to be scanned but which do not interfere with the vision between the scanner and the object to be scanned. The following parameters were selected on the scanner:

- Method: Scanning in window
- Resolution: 3 mm/10 m.
- Quality: 3×
- Scanning with color: Yes

Then, the scanner is placed in different positions with height variation to reach the capture of all data. A total of 14 scanning positions were carried out in approximately 4 hours of data capture.

4.2.2.3 Data Processing. Processing of the data obtained from the Faro Focus S150 laser scanner takes place in the Scene software and involves the following actions:

- Importing the scans.
- Processing the scans: Consists of creating the point clouds of the independent scans, coloring these point clouds from the 360-degree images made by the laser scanner, and searching for sphere targets. Figure 6(b) shows the resulting cloud obtained for the *Holy Christ of the Blood*.
- Registration of the scans: It will be used in an automatic registration method based on sphere targets to obtain the point cloud.
- Clean: Because the Faro Focus S150 laser scanner scans in 360 degrees and although we have used the window scanning method, we must clean the cloud because it captures points from the bottom of the room, which we do not need.

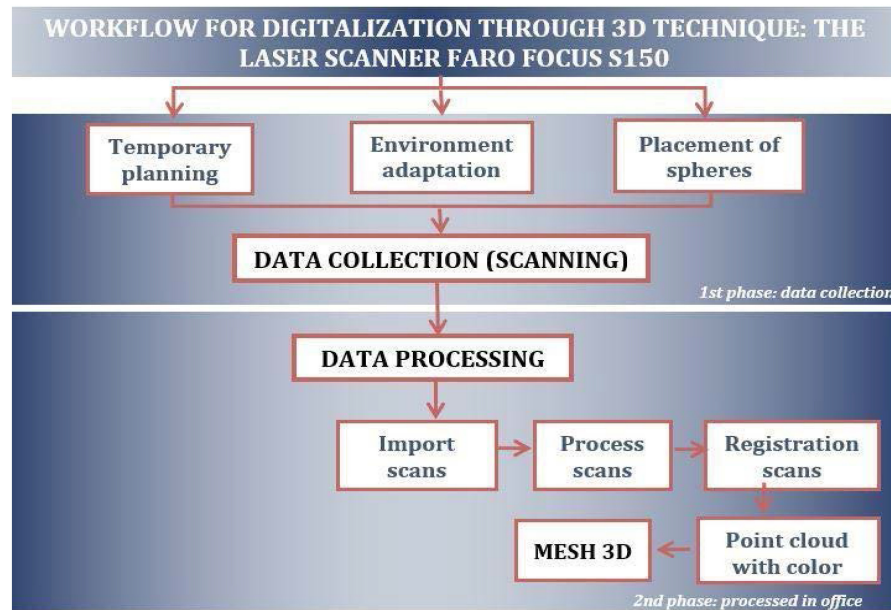


Fig. 8. Workflow diagram for the Faro Focus S150 laser scanner.

- Creation of 3D mesh from selection: Watertight (so that it closes the gaps); generate texture and maximum number of triangles.

The workflow established with the technique of the Faro Focus S150 laser scanner is shown in Figure 8 [22].

5 COMPARISON BETWEEN DIFFERENT 3D SCANNING TECHNIQUES

The results obtained by digital photogrammetry were acceptable, although a lack of precision in detail is detected in the smaller objects and specific details.

In turn, the texture records were also satisfactory, observable on visual inspection. However, the digitization process with this technique is too long, as can be seen in Table 1 and is too laborious to obtain a quality model, as several photographic and verification sessions are necessary in addition to the processing and post-processing time of the data, as described in [19]. For these reasons, there was interest in making a comparison with the laser scanner and structured light scanner techniques.

After detailing the optimal workflow required for each selected scanning technique, our analysis focuses on developing a comparison methodology to evaluate the quality of the results obtained. Regarding the data collection process, the Artec Eva structured light scanner requires connection to a power outlet and a computer, which must also have the specific software installed because the data capture and import are automatic as the object is being scanned. In contrast, the Faro Focus S150 laser scanner does not need to be connected to any computer because it works with a battery and the data is imported later.

Digital photogrammetry is the technique that required the longest capture time, 16 hours, followed by the terrestrial laser scanner, 4 hours, and, finally, the structured light scanner with 1 hour. The captured data have been processed in the specific programs of each of the scanners. The fastest processing is that of the laser scanner, 30 minutes, because the only actions to be performed are processing and recording. Control and repair actions of the 3D mesh geometry are missing, as presented by the Artec Eva structured light scanner software. With this last scanner, the processing time has been 2 hours. However, the control of the data processing is total, from the

alignment, registration, data removal, gap filling, mesh creation, texture, and so on. For a similar resolution, the processing time in photogrammetry is considerably higher than the other techniques, being 3 full days, 8 hours, and 33 minutes [23].

As we can see in Table 1, the total scanning time (capture + processing) varies considerably between techniques. Photogrammetry takes the most time, practically 94% more time than the laser scanner (6% of time) and 96% more time than the structured light scanner (4% of time).

The noise level in the point cloud is also a factor to consider; if it is not cleaned correctly, it can distort areas or geometric characteristics in some areas of the 3D model [24]. Special attention should be paid to the base of the object or floor where it rests and nooks and crannies typical of the sculpture, such as the inside of the legs or hands [25]. In the case of photogrammetry, the introduction of noise from the surroundings is low because chromas were used for the backgrounds that facilitated the generation of masks for the photographs.

However, the noise of detail on the mesh is very high, probably arising from the gloss or varnish of the polychrome of the sculpture itself. Hence, the software creates the irregularities observed in the model in Figure 9(b). In the case of scanning with structured light, the inclusion of noise from the environment is medium, observed at the base of the object and between the fingers. In the case of scanning with structured light, the inclusion of environmental noise is medium, observed at the base of the object and between the fingers only.

The noise introduced by the laser scanner is high, as it shows points on the floor where the object rests, environmental elements, spheres, and other elements. The elements that do not belong to the model and noise generated must be manually removed via digital photogrammetry and laser scanner [26]. The structured light software Artec Studio 14 has an automatic cleaning process for small objects with a high-quality algorithm and automatic base detection, which simplifies and facilitates the final closing of the mesh.

There are great differences found in comparing the point clouds and models obtained by each of the techniques. First, the largest point cloud is that generated by the Artec Eva structured light scanner, followed by the photogrammetry dense point cloud with almost 50 million points, compared with 1.8 million points in the Faro Focus S150 laser scanner.

Second, the meshes generated from the point clouds of the different techniques again show great differences. The mesh that provides a greater number of polygons is that of the Artec Eva structured light scanner, with 51,163,728 points, although this is reduced to 10 million in order to be able to make comparisons between digital photogrammetry, the structured light scanner, and the real object in the following section. Third, there is the 3D mesh obtained by digital photogrammetry, with almost 9,969,242 polygons. Finally, with great difference again, there is the mesh generated by the Faro Focus S150 laser scanner, with 584,308 polygons. There are also small differences in the volumes enclosed by the meshes, a smaller volume of 0.066 m³ in the mesh of the structured light scanner, probably because it has a tighter geometry. This is followed by the 0.068 m³ of mesh obtained by digital photogrammetry, probably increased by the noise and roughness present on the surface of the same, as can be seen in Figure 10.

The difference between the volumes of the different scanning techniques is 0.003 m³, approximately 3 liters of water, a more than considerable difference. It should be clarified that the resolutions and level of detail of digital models do not depend exclusively on parameters such as the number of polygons; rather, they depend on the size and arrangement of those polygons [27]. There is a clear relationship where the techniques capable of generating a greater number of polygons—and, therefore, smaller polygons—are those in which greater resolution and level of detail are obtained, in addition to better adaptation of these polygons to the geometric shape of the object.

On the other hand, the textures generated by the different scanning techniques also show differences. The texture of digital photogrammetry is 4096 × 4096 pixels, with a resolution of 120 dpi. It presents a highly fragmented surface structure of the object and fills the gaps with a general fading of a shade similar to the color of the larger surface [28]. The texture obtained by the structured light scanner is also 4096 × 4096 pixels, with a lower resolution of 96 dpi. As can be seen in Figure 11, this texture also shows a surface structure of the object.



Fig. 9. Geometric detail of the faces of the 3D models of the different 3D scanning techniques. (a) Structured light scanner. (b) Photogrammetry. (c) Laser scanner.

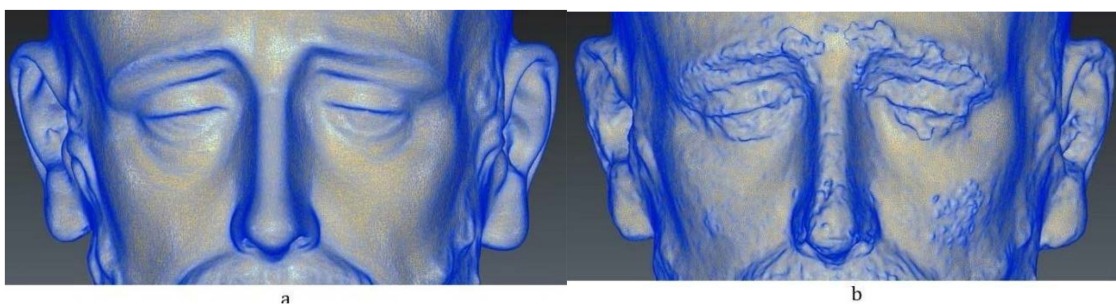


Fig. 10. Theoretical detail of the wire model of the different 3D scanning techniques. (a) Artec Eva structured light scanner. (b) Photogrammetry.

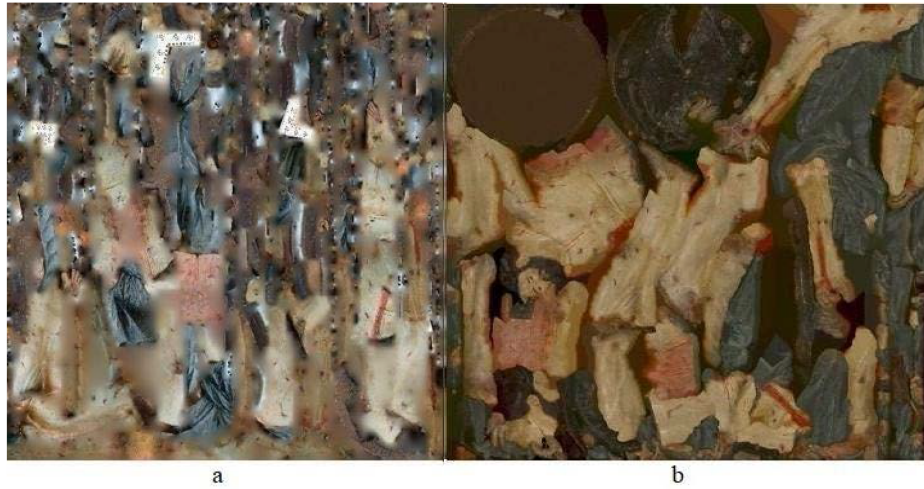


Fig. 11. Texture detail. (a) Digital photogrammetry. (b) Artec Eva structured light scanner.

However, this is less fragmented than that of digital photogrammetry. It also fills the gaps with a general fading of a shade similar to the color of the larger surface. Both textures can be exported in the .jpg or .png format, with the size of the digital photogrammetry being 1.67 MB and the structured light scanner 1.24 MB. The Faro Focus S150 laser scanner does not allow you to export a separate texture for processing a mesh with the maximum possible number of triangles.

The color fidelity to the original object has to be checked, as both techniques show differences in the color tones of the textures. To this end, we decided to check these differences by using a spectrophotometer or Spectro colorimeter. A priori, through the subjective visual inspection, more shadows and brightness are observed in the texture obtained with the digital photogrammetry than in the texture obtained by the structured light scanner because, having a built-in flash, the control of light and color is much more faithful to the original.

To conclude, it can be said that in terms of volume and geometric precision, the Artec Eva structured light scanner and digital photogrammetry are the techniques with the highest precision and resolution, best adapted to the real geometry of the object.

Therefore, we discard the use of terrestrial laser scanner for the digitalization of this type of heritage and we will focus the interest of our comparison on the first two techniques. Specifically, our study will address the degree of quality of scale and color of the textures provided by both in relation to the real object under study, the polychrome wood sculpture of the *Holy Christ of the Blood* by Bussy.

6 QUALITY COMPARISON BASED ON SCALE AND COLOR COMPARISONS BETWEEN THE GENERATED 3D MODELS AND THE REAL CARVING

6.1 Scale Comparisons

To complete the comparative analysis between the techniques of digital photogrammetry and structured light scanning, the scale of both models has been checked. Since digital photogrammetry does not capture the scale of the object, it was necessary to use scale bars to scale the 3D model after processing [26].

As can be seen in Table 2, the method is totally effective in providing the real scale to the photogrammetric 3D model because in the data obtained, there is a difference of only 2 mm, which we could perfectly attribute to human error. Similarly, it can be seen that the scale obtained from the 3D model of the structured light scanner is totally accurate and it is not necessary to scale the object after processing. The comparison of the dimensions

Table 2. Distance Measurements Over Size in Each of the 3D Digital Models and Differences

Measurement reference	Real object (cm)	Photogrammetry (cm)		Structured light scanner (cm)	
		Measurement	Difference from real	Measurement	Difference from real
Horizontal back plate	8.9	9.1	-0.2	8.9	0
Foot to finger	7.7	7.8	-0.1	7.7	0
Cloth folds	7.5	7.5	0	7.5	0
Arm between cuts	27.7	27.8	-0.1	27.6	+0.1

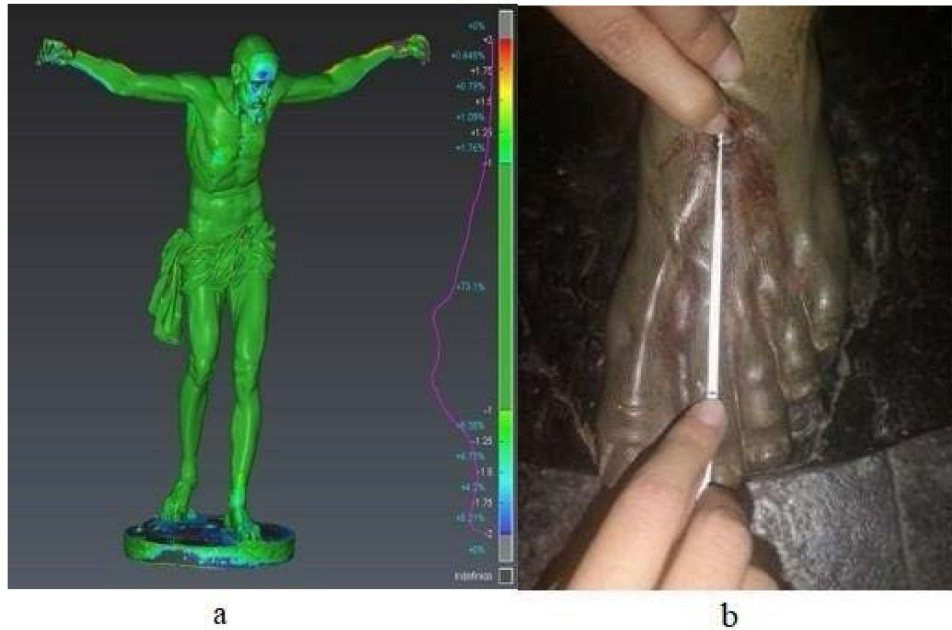


Fig. 12. (a) Error deviation analysis. (b) Taking manual measurements.

has been made by taking the same measurements on the real object and on the 3D models. A more precise method to obtain and check where the scale differences between the 3D models are is the dimensional control analysis by standard deviations [29]. Using the 3dreshaper[®] software, it is possible to carry out a comparison of the photogrammetric 3D model against the structured light 3D model. The deviation parameter of ± 2 mm error, which was the largest distance obtained in the manual metric analysis explained earlier, is entered to check more graphically and visually where these differences are.

As we can see in Figure 12, in red, a difference of +2 mm can be seen in the arms, thus comparing the result obtained through manual measurement. Also, a difference of -2 mm can be seen mainly in the face of the Christ, which is shown in blue. This difference can be attributed to the lack of geometry and resolution in the small details that we have been able to observe in the photogrammetric model, as shown in Figure 10. However, a large part of the model can be seen in green, where the scales of both models are practically exact, being between ± 0 to ± 1 mm in more than 73% of the model; 27% would be between ± 1 to ± 2 mm in error [30].

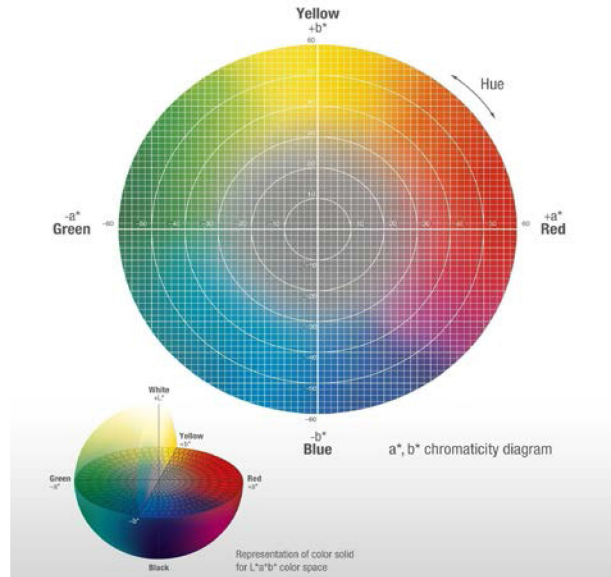


Fig. 13. CIE Lab/Hunter Lab chromaticity diagram (Source: Konica Minolta).

6.2 Verification of the Color Quality of the Textures Generated

The use of objective measurement techniques has been chosen for registration and color comparison. The subjective, more inaccurate, measurements are based on the comparison of visual perception between samples and reference standards. Objective color measurement consists of recording the reflectance of an object in the visual range through the use of equipment such as the colorimeter or spectrophotometer.

The colorimeter emulates human vision by collecting information exclusively in three wavelengths (red, green, and blue) by means of three receptor photocells. The spectrophotometers collect more information in the whole visible spectrum and through algorithms convert it into values equivalent to the perception of the human eye [31]. Furthermore, the use of this equipment ensures reliable color dating because the potential risks of differences between spectra throughout the day, with different light sources and the intervention of different human observers, are avoided.

In our case, the Minolta Conic Spectrophotometer CM-700d with the calibration plate CM-A177 has been used. For the representation of the color samples collected, the Hunter Lab color space has been chosen, which normalizes the CIE Lab values with respect to the characteristics of the illuminant used to capture them. The age of the carving rules out the use of illuminants that represent artificial light sources (e.g., incandescent or fluorescent light), opting for the use of type D65 ($T = 6504K$) which is equivalent to average daylight, including the ultraviolet wavelength region. As can be seen in Figure 13, the dynamic range of variables in the Hunter Lab space is:

$$0 < L < 100, -60 < a < 60 \text{ and } -60 < b < 60.$$

Our methodology initially consists of selecting color reference points along the geometry of the size. A preliminary analysis leads us to consider four shades to be characterized for later comparison: skin, cloth, blood on the side, and beard. However, the geometry of the beard is so abrupt that it is difficult to extract reliable color samples due to the size and planar geometry of the measurement mask of the spectrophotometer used.

Finally, four measurement points are selected on flat surfaces of the size geometry: one on the skin (near the knee of the left leg), one on the cloth, and two in the blood that flows from the side, one next to the sore and one



Fig. 14. (a) Sampling by spectrophotometer. (b) Identification of measurement point on the textures of the 3D models.

next to the cloth. The samples are obtained by means of the spectrophotometer mask with the smallest hole, 3 mm in diameter. Each measurement made consists of obtaining the average of the light captured on this circular surface. The result is the 3 coordinates of the Hunter Lab space, which we call L_r , a_r , and b_r .

The next step consists of locating with great precision the equivalent measurement points on the texture maps of each 3D digital model (.jpg or .png image files). As can be seen in Figure 14(b), software such as Blender allows this location to go from 3D to 2D with great precision. Finally, using image editors such as Photoshop measurements of the color on the texture can be made. The resolution of this image determines the size of the matrix equivalent to the area of measurement on which to make the average color. In our case, as the resolution of each of the textures is 96 and 120 dpi, structured light and photogrammetry, the area of a circle of diameter 3 mm is approximately equivalent to a matrix of 11×11 and 14×14 pixels, respectively.

Therefore, once the point has been located, an average matrix of 11×11 pixels is selected in both textures since, when in Photoshop, these dimensions jump to 31×31 . Finally, the value of the coordinates L , a , and b is extracted.

Once we have the reference L_r , a_r , b_r coordinates in each point and the homologues extracted from each texture image L , a , b , we proceed to the comparison through the calculation of the color difference values:

$$\Delta L = L - L_r \quad \Delta a = a - a_r \quad \Delta b = b - b_r$$

to finally obtain the so-called total color difference

$$\Delta E = \sqrt{(\Delta L^2 + \Delta a^2 + \Delta b^2)}.$$

The lower the value of ΔE , the greater the correlation between the texture and the real model and, therefore, the higher the color quality of the model [32]. The polar representation of the Lab coordinates on the

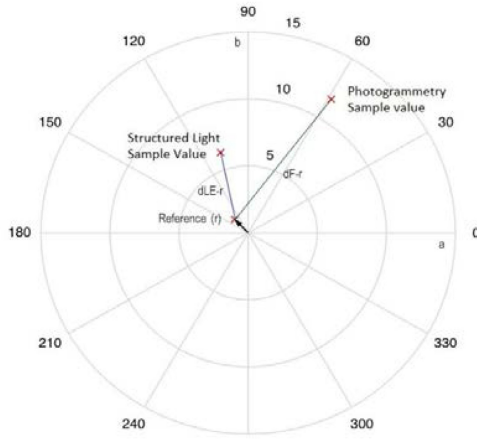


Figure: Polar representation and comparative analysis of color samples in the cloth area

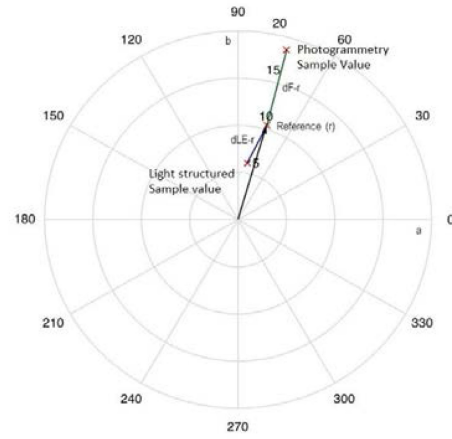


Figure: Polar representation and comparative analysis of color samples in the skin area near the left knee.

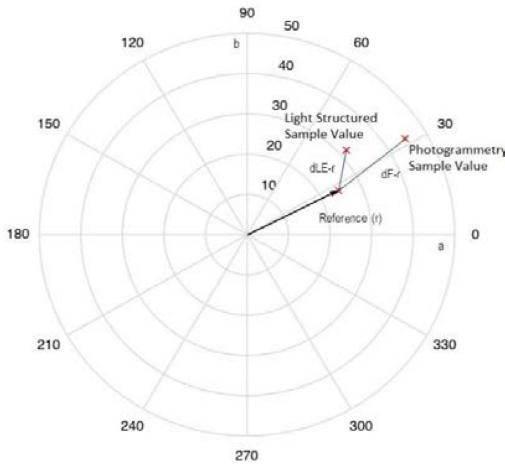


Figure: Polar representation and comparative analysis of color samples in the area of the blood next to the sore

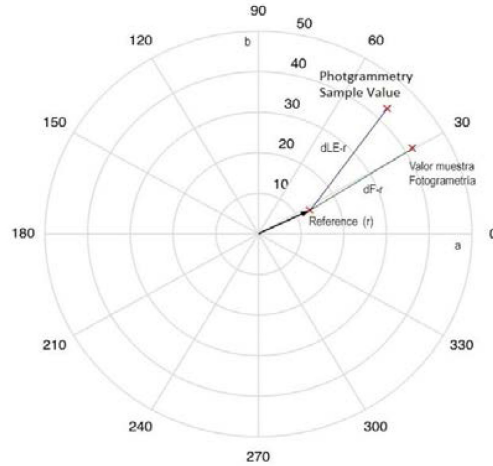


Figure: Polar representation and comparative analysis of color samples in the blood area next to the cloth

Fig. 15. Polar representation of the samples at each location and distance vector plotting between them.

chromaticity diagram gives us a graphic approach to the analysis of the comparison. Each color sample represented corresponds to a point, characterized by its hue:

$$(\text{Hue: } \arctan(b/a)), \text{ and chromaticity (C: } \sqrt{(a^2+b^2)}) \text{ or saturation (S = C/L).}$$

The distance between the reference sample and its counterparts in the textures of the digital models obtained by photogrammetry ($dF-r$) and laser scanning of structured light ($dLE-r$) is another parameter that helps to determine the degree of correlation between the models and reality, in this case discarding the information on the brightness or luminance of these sensations. Figure 15 shows these calculations graphically on polar representation diagrams.

The results of the comparison calculations are presented in Table 3. It can be seen that the texture of the model generated by structured light has a greater correlation with the real color, measured by the spectrophotometer, in

Table 3. Calculations for Color Comparison between Spectrophotometer Samples and 3D Models

COLOR SOURCE	MEASUREMENT	ΔL	ΔA	ΔB	ΔE	DISTANCE FROM COLOR REFERENCE (DLE-R/DF-R)
Structured light	Skin	2	8	8	11,66	11,49
Photogrammetry		-4	-12	-13	17,85	17,40
Structured light	Cloth	-1	5	5	7,08	27,01
Photogrammetry		-4	-16	5	17,33	16,87
Structured light	Blood (near cloth)	18	25	30	42,81	38,84
Photogrammetry		6	-10	-1	11,75	10,11
Structured light	Blood (near sore)	2	10	7	12,54	12,38
Photogrammetry		14	3	13	19,38	13,39

most of the measurement points, with the exception of the blood sample near the cloth, in which photogrammetry presents better results.

This result is not surprising due to several factors. First, the LED illuminants used by the spectrophotometer and the structure light scanner employed are spectrally similar white lights. In addition, these sources have a highly homogeneous illumination pattern on the samples, which undoubtedly favors the achievement of high-quality textures. In the case of photogrammetry, although the results are satisfactory, a greater deviation can be seen as a result of the heterogeneity of the lighting process. As the whole of the carving has to be covered, the complexity of the process is much greater because different illuminants or light sources are used, to which the handicap of minimizing shadows is added in order to obtain better processing not only of the texture but also of the geometry.

7 RESULTS

The complete review of the main processes and techniques of 3D scanning and the comparative analysis of the 3D models obtained for the carving of the *Holy Christ of the Blood* give the following results of the present research:

- The intensive use and experimentation allow definition of the optimal workflows for the use and execution of each of the different 3D scanning techniques most used in heritage, which could be used as a basic guide for the digitization of heritage objects. The comparison between these represents a first approximation to the identification of the most appropriate technique.
 - A table-type structure is provided for the refined description that facilitates a complete initial comparison between scanning techniques.
- Objective arguments are provided to reinforce the choice of specific 3D scanning techniques over the others, based on the summary tables and results displayed numerically and graphically.
- An unprecedented methodology has been developed for the verification of the quality of 3D models based on the comparison with the real object on the basis of the comparison between scale and texture:
 - The comparison of scales between the 3D models through manual metric measurements on the object with digital measurements of the 3D models.
 - The scientific analysis of the dimensional control of the 3D models obtained by standard deviations for checking the scale, the manual metric measurements taken, and the level of detail of the 3D models.
 - The analysis of textures and color differences obtained by different 3D scanning techniques using spectrophotometers.

- The use of the terrestrial laser scanner is ruled out, and the structured light scanner is identified as the technique with the highest geometric and colorimetric quality results for the digitization of sculptural heritage.

8 CONCLUSIONS

The main conclusions that we have obtained from this research lead us to establish precise workflows for each of the digitization techniques studied, foreseeing both the shape and/or size of the object, the place where it is located, and the time for carrying out the work, as well as the steps and recommendations to be followed in the digitization process, obtained through our experience in this sector.

It has been demonstrated throughout the article that not all 3D scanning techniques have the same precision and accuracy and it is up to the user or digitizer's experience to choose which 3D scanning technique to use. It has also been possible to show numerically and graphically that digital photogrammetry and structured light techniques are the most accurate techniques for documenting heritage. Obtaining the structured light technique provides better geometric detail and resolution in small details than digital photogrammetry.

We can assure that the structured light scanning technique obtains better geometries by obtaining a larger point cloud and the adaptability of its triangles when creating the 3D mesh is much more reliable to the original object than the other techniques. However, it also has its limitations since it is a short-range scanner, which limits the size of the elements to be scanned, not being competitive with other scanning techniques such as digital photogrammetry or the terrestrial laser scanner in the registration of large elements.

We conclude definitively that the structured light technique for the 3D scanning of religious imagery, thanks to the results obtained in this article, is the most appropriate and precise for use in the capture and 3D documentation of the sculptural heritage. It should be considered that if the same study is replicated in other objects or with the use of other devices or scanners, different results may be obtained. A technique that in this study has been considered valid for one type of heritage can be invalid for another and vice versa. Finally, some considerations should be added if the study is carried out again, such as a color checker for the white balance of the photogrammetry images, and a similar study should also be carried out with another terrestrial laser scanner to ensure or totally rule out its use for the replication of a heritage object of these characteristics.

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