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Metrological 3D documentation of the Holy Chalice of Valencia Cathedral: Quantitative geometry for cultural heritage research

Nicolás D. Niquet-Herrero[a], Stephan Kröner[b], Juan Valcárcel-Andrés[c], Xavier Mas-Barberà[c,*]

[a] SNBR-AKELOE Company, 3D Technologies Applied to Cultural Heritage, Conservation and Restoration of Cultural Heritage- Universitat Politècnica de València, Spain
[b] Conservation and Restoration of Cultural Heritage, Spain
[c] Instituto Universitario de Restauración del Patrimonio, Universitat Politècnica de València Spain

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ABSTRACT

This article presents a metrological case study of the Holy Chalice preserved in Valencia Cathedral, Spain, using high resolution 3D measurement to provide reliable geometric data for cultural heritage research. The Holy Chalice is a unique piece due to its symbolic nature and the properties of its materials. It combines a banded agate cup with variable translucency and a later gold mount with gemstones, pearls, and an agate base. This complex material configuration poses challenges for optical digitisation, particularly where reflective and translucent surfaces affect measurement stability. The main objective is to deliver reproducible information on size, morphology, and volume derived from a 3D model, supporting multidisciplinary analysis by archaeologists, restorers, gemmologists, and historians, with particular relevance for dating and comparative assessment. The intervention was conditioned by the emblematic character of the object and its delicate state of conservation. Data acquisition was carried out with a high performance portable laser scanner, MetraScan3D by Creaform, using an external triangulation module and a configuration suited to highly reflective surfaces. The resulting 3D model enabled quantitative analysis and the production of a physical replica, allowing examination without direct handling of the relic. The study shows that this non-invasive approach is effective for the digitisation and metrological analysis of delicate historical objects with unfavourable surface typologies.

1. Introduction

The Holy Chalice, the subject of this research, is a venerated relic kept in the Cathedral of Valencia (Spain) (Fig. 1). The piece holds a transcendental importance in the history of art and religion, as it is attributed to an origin dating back to the 2nd century BC and the 3rd century AD [1,2], closely linked to the figure of Jesus Christ, making it an object of fascination for scholars and believers alike. Historical studies and scientific analyses conducted to date on the relic have shed light on its origin and significance in Christian tradition.

The authenticity of this cup has been the subject of lively debates and a challenging topic that needs to be justified. The origin of this Holy Chalice is shrouded in legend and tradition. It is believed to have been used by Jesus Christ during the Last Supper, making it an object of great veneration for Christians. Findings by experts in sacred art and archaeology have provided clues about the authenticity (history, iconology, symbolism, typology, design, or pattern) and possible provenance of the cup [1–12].

The history of the Holy Chalice dates back to the dawn of Christianity and spans centuries until its current location in the Cathedral of Valencia. According to tradition, this cup was taken to Rome by St. Peter. It was then guarded by successive Popes until the reign of St. Sixtus II, who, through his deacon St. Lawrence, sent it to his homeland of Huesca in the 3rd century to protect it from the persecution of Emperor Valerian. During the Muslim invasion in 713, the relic was hidden in the Pyrenees region, passing through various locations until it reached the monastery of San Juan de la Peña (Huesca), where it is mentioned in a document from 1071 as a precious “stone chalice.” In 1399, it was delivered to King Martin I of Aragon, who kept it in his royal residences until his death in 1410. In 1424, King Alfonso V the Magnanimous transferred the royal reliquary to the Palace of Va-

* Corresponding author.
E-mail addresses: nikodidier@gmail.com (N.D. Niquet-Herrero), stephan.kroner2013@gmail.com (S. Kröner), jvalcara@crbc.upv.es (J. Valcárcel-Andrés), jamasbar@upvnet.upv.es (X. Mas-Barberà).

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Fig. 1. (a-b). Aula Capitular, now the Chapel of the Holy Chalice, Metropolitan Cathedral–Basilica of the Assumption of Our Lady of Valencia (Spain). a) Alabaster altarpiece with the niche containing the Holy Chalice in its central part, general and detail of the reliquary urn that protects the relic, made up of: chalice (cup, upper part), stem (middle part) and foot (lower part); and, view of the relic with light projected from the lower and zenithal area; b) Detail of the agate cup that is the subject of this research, detail of the break suffered in 1744 and the subsequent adhesion (zenithal angle lighting), and detail of the whitish stain observed through UV-induced visible fluorescence imaging.

lencia, and in 1437, during the King's stay in Naples, it was delivered along with other relics to the Valencia Cathedral, where it has been venerated and preserved since then. During historical events such as the War of Independence and the Spanish Civil War, the Holy Chalice was moved to protect it from destruction. However, its public display in the former Chapter House, now the Chapel of the Holy Chalice, in 1916 allowed it to be widely disseminated. Pope John XXIII granted plenary indulgence on the day of its annual feast, while Popes John Paul II and Benedict XVI celebrated the Eucharist with the Holy Chalice during their visits to Valencia in 1982 and 2006, respectively. This symbol of faith, history, and tradition has endured through the centuries, becoming a distinctive emblem of devotion and veneration for the faithful. It is a cup of incalculable religious value, and its size, shape, and unique colouration distinguish it from other cult relics.

Most of the studies and analyses to date on the cup of the Holy Chalice have focused on aspects of the material (through photogrammetric records such as those carried out in 2015 by the company Steadpro and, again in 2025 by IT3D Technology SL, which produced digital clones of the relic), general dimensions, and archaeological and historical characteristics; however, specific details such as wall thickness, volume capacity, and surface irregularity have not been addressed in previous reports.

The study was approached from several perspectives: i) 3D metrological study of the Holy Grail using advanced three-dimensional scanning and modelling techniques, obtaining precise measurements in fractions of millimetres; ii) vertical and horizontal segmentation of the cup, taking wall thickness measurements and representative details of the entire object; iii) interpretation of results, comparing wall thickness in different parts of the cup and providing data on use (volume capacity) and handling over time (state of conservation); and iv) correspondence models (comparison with other existing pieces with analogous measures and shapes, polished surface techniques, among others), allowing for well-founded and meaningful information.

This study was conducted within the research project "Characterisation of the Holy Chalice of Valencia: Mineralogical, Gemmological, Glyptic, Photographic Study, and 3D Registration", promoted by the Spanish Centre of Sindonology and the Chapter of Valencia Cathedral. The work adopts a practical multidisciplinary perspective and presents a metrological case study based on 3D registration and quantitative analysis.

1.1. Research aim

The primary aim of this research is to create an accurate and detailed 3D numerical model of the Holy Chalice of Valencia, using advanced metrology and laser scanning techniques. This model will provide essential data on the Chalice's dimensions, morphology, enabling a deeper understanding of its historical, religious, and artistic significance. Furthermore, the study aims to support future research, conservation efforts, and educational engagement by offering a precise, non-invasive method of documenting cultural heritage artefacts of similar significance. Finally, the research seeks to support conservation efforts, enhance future archaeological and scientific studies, and facilitate broader public engagement through digital preservation and educational initiatives.

2. Experimental part

2.1. Subject of the study

The subject of the study is described as a chalice of classical form with a foot and/or base that supports the whole, a stem that rises from the foot, and a slightly flared cup with a simple rim like a thin ribbon at the top of the mouth. The banded agate stone cup is the most significant part, as both the stem and base are much later additions, assembled in medieval times [1,9].

The cup is carved from banded agate stone, a stone that presents brownish-red and black tones. Recent preliminary studies suggest that the agate comes from areas of South Asia and was dyed using the ancient 'honey caramel' hot technique, achieving an effect that simulates more precious stones such as carnelian or brownish agate [13]. This variety of agate is distinguished by its translucency and parallel and symmetrical bands. Gemmological studies indicate that the piece was not formed as a geode but originated as the filling of a crack [14]. The irregularity in the carving of the cup suggests an artisanal work that adds an element of authenticity and antiquity to the relic and has influences from ancient Mediterranean craftsmanship. This irregularity is the result of the technique used by ancient artisans, who, with rudimentary tools but exceptional skill, carved and polished the stone to create shapes and patterns. This imperfection in the carving not only adds historical character to the relic but also reveals the craftsmanship in carving this type of hard stone. The choice of banded agate as the material for the relic may have symbolic connotations. Light strikes in a particular way due to its crystalline structure and the colour bands, which, thanks to their translucency, allow light to penetrate the stone, creating unique visual effects (Fig. 1a). The beauty and rarity of this stone may reflect the sacredness and importance of the object it represents.

An archaeological study conducted in 1960 by Dr. Antonio Beltrán Martínez, a Spanish archaeologist specializing in the study of medieval history and art, established its authenticity and possible connection with the Last Supper of Jesus Christ. Detailed archaeological, historical, and scientific analyses of the relic, including radiographic tests and metallurgical analyses, concluded that the chalice consists of an agate cup dating from the late Roman period (2nd-1st centuries BC), with a base and handles added later during the medieval period [1]. He also identified marks and characteristics on the relic that suggest its antiquity and authenticity. Additionally, he indicated the size of the cup, which would be approximately 5.5 cm high and 9.5 cm in diameter at its mouth.

On the other hand, Professor Ferran Arasa (2014) dates the cup to between the 1st century BC and the 3rd century AD. He notes that the carving of the cup is "quite" irregular and that "in competition with glass cups, artisans strove to make the cups thinner to appear more transparent, imitating glass." This statement is justified when observing the cups in the British Museum, which, with a thickness of 1.5 mm, are dated between 0–50 AD. To make such thin cups, the technique of stone cup carving must have "refined somewhat, as logically, such an irregular thickness as that of the Holy Chalice cannot be achieved with such a fine thickness." Evidently, the artisans working with hard stones during the period from the 3rd century BC to the 1st century AD used a variety of simple but effective tools made of wood and metal to carve and shape cups and objects (chisels, gouges, hand-turning tools, scrapers, and abrasive stones) [9,15–17], although it is important to consider that both the tools and stone working techniques had to adapt to the demands of the high-ranking customers.

The state of conservation of the cup of the chalice is acceptable; however, it presents two notable damages from its historical journey. On one hand, an incident occurred in 1744 during the Good Friday services, where the chalice fell to the ground, splitting into two parts and in turn into several small pieces, in addition to a small loss at the top of the mouth. The pieces were reassembled, and the relic was restored as it is seen today. The intervention reveals a certain mismatch between the smaller pieces, which, despite this, does not prevent it from fulfilling its Eucharistic function. On the other hand, it presents a whitish stain and/or surface discolouration that does not penetrate the wall of the cup [14] and originated before the second half of the 17th century, according to existing graphic sources in the Valencia Cathedral Museum [18] (Fig. 1b).

3. Methods and instrumentation

The use of new registration and printing technologies for the study and treatment of Cultural Heritage is well known [19–22]. These advanced three-dimensional scanning and modelling techniques involve the use of various tools and instruments very useful for determining properties and aspects of works of art.

3.1. 3D modelling and reproduction techniques

3D data acquisition techniques allow accurate information to be obtained without physical contact, but their usefulness varies depending on the objective: digitisation for visualisation or metrological capture. While digitisation is aimed at generating visually accurate models (e.g. for dissemination or virtual reproduction), metrological acquisition focuses on obtaining exact three-dimensional coordinates, ensuring reliable measurements for scientific analysis. These techniques are based on optical triangulation methods, which can be passive or active.

Passive systems (such as photogrammetry) depend on ambient light and reconstruct geometry from 2D images, making them very effective for generating visual models, although they have limitations when high metric accuracy is required. In contrast, active systems project their own radiation, structured white light or laser, and can provide three-dimensional data in real time with increased metrological control, which is often advantageous for small, delicate, or geometrically complex artefacts.

Both passive and active systems can operate statically or dynamically. Static systems record information from fixed positions, which guarantees stability but limits access to hidden areas or recesses. Dynamic systems, on the other hand, allow the emitter and receiver to be moved around the object, adapting distances and angles to avoid geometric shadows and obtain complete coverage, an essential aspect in three-dimensionally complex artefacts such as the Holy Chalice [23–28].

Among active systems, triangulation using structured white light offers good accuracy for small parts, but its effectiveness decreases with reflective or translucent materials that distort the projected pattern [29–32]. In contrast, proximity laser scanning provides greater point density and accuracy, although it requires additional positioning systems. Even so, for small artefacts such as the Holy Chalice, these limitations can be managed without compromising the integrity of the object.

Digital models derived from the record enable the creation of physical replicas through additive manufacturing, which are of particular interest. From the metrological model obtained, it is possible to produce a solid piece that facilitates handling, geometric verification and formal comparison, without the need to directly intervene in the original. In this sense, additive manufacturing is integrated as an extension of the metrological process, rather than as an exercise in visual reproduction. At the same time, obtaining 3D digital models derived from the record opens up the possibility of generating study alternatives without altering the originals, allowing virtual manipulation, detailed analysis and simulations. The incorporation of additive manufacturing technologies in the heritage field has reinforced this approach, as physical reproductions based on digital models allow for the identification of formal details, understanding of creation processes and testing of proposals without risk to the work. Additive manufacturing techniques have evolved significantly in recent years, enabling the creation of solid pieces from virtual models [20]. Among the most widely used technologies are stereolithography (SLA), selective laser sintering (SLS), fused deposition modelling (FDM) and photopolymer injection. These technologies use different materials (powders, solid filaments or liquid resins) and are based on the successive deposition or solidification of layers [33,34]. Particularly, stereolithography offers significant advantages for heritage: high precision, good production speed and excellent surface finishes, making it particularly suitable for small parts or those with intricate details [19,21,32].

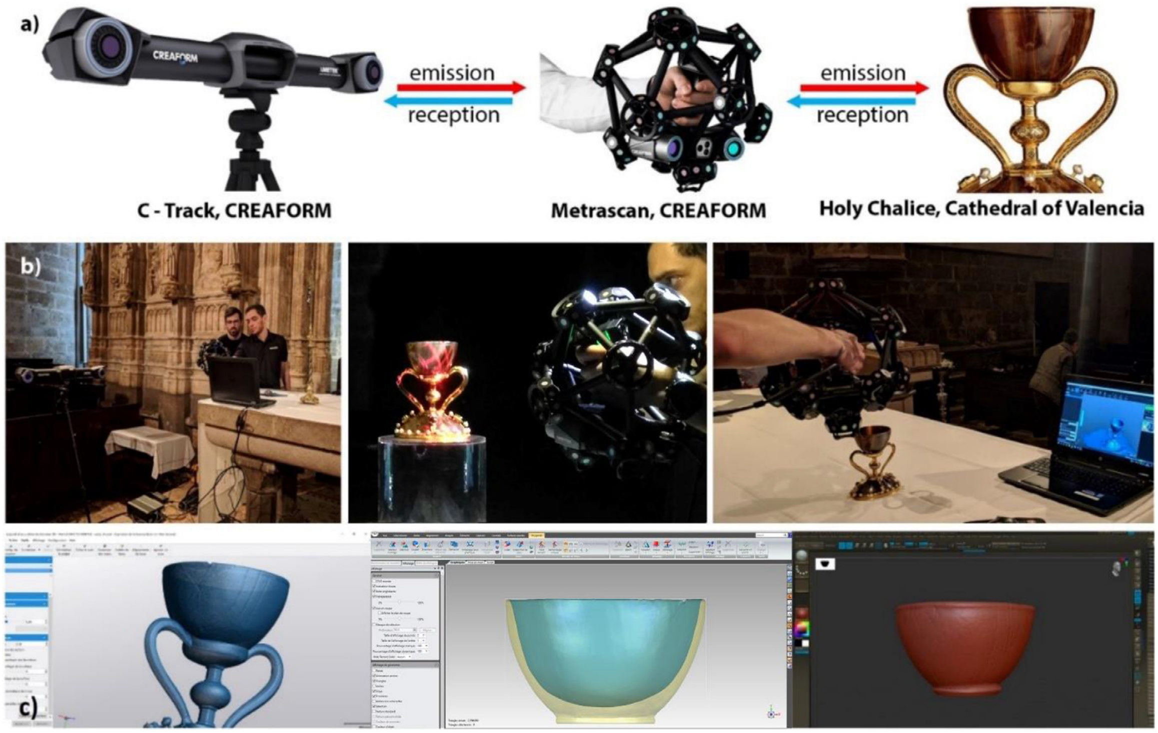

Fig. 2. (a-c). MetraScan 3D scanner from the Canadian company Creaform. a) External triangulation module (track) and laser scanner without the need for magnetic targets on the work to be recorded; the targets are on the tool itself and allow two-way 'communication'. b) Calibrating the system, 3D data acquisition and detailed view of the active triangulation on the computer screen; c) Vxmodel® software (Creaform), Geomagic Wrap® software (3D Systems) and ZBrush® software (Maxon®).

3.2. Application of the 3D metrology and reproduction techniques on the Holy Chalice analysis

The selection of registration tools for this study of the Holy Chalice was made considering both the intrinsic factors of the piece (material properties and conservation state) and extrinsic factors (exhibition method, study conditions, among others). As for intrinsic factors, the following were taken into account: i) the banded agate stone material presents translucency, light refraction, absorption, and reflection [35]; ii) the gold stem presents reflection; and iii) the agate base, gold, precious stones, and pearls exhibited refraction, reflection, absorption, and light transmission. On the other hand, regarding extrinsic factors, the following premises were considered: i) minimal handling of the piece; ii) no contact with the piece, avoiding the use of positioning targets (or opacifying products, among others); and iii) relatively short intervention time due to the urgency in developing the 3D registration limited by the Chapter of the Valencia Cathedral (Fig. 2).

In this context, several 3D registration tools were considered for studying the relic, each with its advantages and disadvantages for final selection. On the one hand, photogrammetry, although widely used in the documentation and study of Cultural Heritage, especially for close range images acquisition, has great potential to generate digital twins with very high visual fidelity, particularly when integrated into multimodal studies that combine different remote sensing techniques to provide a broader and more detailed source of information about an object [36,37]. We did not adopt this technique because the research was framed strictly as a metrological investigation, in which the surface appearance of the material was not considered relevant information. Accordingly, no colour texture is reported here, and the model is not intended for photorealistic rendering of material appearance. Nevertheless, an exhaustive photographic survey was carried out in parallel, in case a passive reconstruction had been required. In addition, the data acquisition had to be conducted in a single session, so it was essential to prioritise an active triangulation workflow, particularly as a high-quality photogrammetric model had already been generated previously [38].

On the other hand, structured white light scanning produces models with good metrological precision, supports the capture of small scale elements, enables dynamic triangulation and, in some cases, also allows texture capture [39]. However, because of reflection, refraction and absorption phenomena generated when the white light pattern is projected onto certain surfaces, it would be necessary to apply opacifying products over the entire surface to ensure adequate data acquisition [40]. This option was rejected because it was incompatible with the artefact's heritage value. Although most scanners allow the shutter settings to be adjusted, within the limits of each device, to mitigate difficulties arising from reflective materials, this adaptation may not match the performance of controlled lighting and polarisation in dedicated photogrammetric set-ups.

Conversely, close range laser scanning, also based on active triangulation, uses laser scanners with metrological precision on the order of tenths of a millimetre. These systems, also available in portable formats, allow the operator to move around the object, adjusting acquisition distances and angles to cover all recesses. They also make it possible to adjust the shutter settings of the triangulation sensors to control the laser's incidence on the recorded material, always within the limits of each tool. However, they have two common disadvantages, namely the need to place targets on the object or in its immediate surroundings, and the interaction of the laser with certain materials, such as those present in the relic. Even so, given the object's small size, it is possible to perform the data acquisition without placing targets directly on its surface, positioning them only around the piece. In recent years, tools have been developed that replace the traditional red laser with a laser whose wavelength lies in the ultraviolet range, enabling significantly better performance when capture complex surfaces.

In this context, for the acquisition of the relic, the close range laser scanning system enabled the capture of reflective surfaces with sub-millimetre precision, 0.04 to 0.025 mm, using an external triangulation module, C Track, which distinguishes it from conventional laser scanners. Using two calibrated triangulation cameras aligned with the positioning targets integrated into the scanner, the MetraScan was spatially tracked, avoiding the need for targets on or around the relic. The scanner incorporates two triangulation cameras which, together with the projection of 14 laser crosses, recorded the surface. Data acquisition was performed with Vxelements® (Creaform), which generates a polygon mesh dynamically during measurement. Post-processing was carried out using Vxmodel® (Creaform) and Geomagic Wrap® (3D Systems), and ZBrush® (Maxon) was used for local mesh operations required by the levelling workflow described in Section 5.1. ZBrush is primarily designed for organic modelling and UV mapping [20], and was used here for dense mesh handling and controlled masking operations. The workflow enabled real time monitoring during acquisition and supported the generation of a high resolution geometric model suitable for subsequent metrological analysis. The processes and software used are widely adopted in the data acquisition and processing of 3D data in cultural heritage documentation and conservation practice [19,25,29,31,40–46].

Finally, the printing of the digital 3D model was carried out using a Form3® printer from FormLabs®, based on Low Force Stereolithography (LFS)™ technology with preForm software, .STL file format, 250 mW laser power, 85-micron laser spot diameter, layer thicknesses between 23 and 300 µm, and a maximum resolution of 25 µm. It is a stereolithographic (SLA) printer that uses a liquid photopolymer resin; specifically, the basic Grey V4 FormLabs® resin was used. The printer operates by processing the print file (containing the 3D model to be printed) and analysing which areas need to be illuminated to solidify the resin and which areas should remain liquid. Once the printed model is obtained, the piece is cleaned, removing any residual liquid resin and supports.

The methodological process of registering and 3D printing the cup was planned according to: i) assembly and installation of components and calibration of the scanner on-site in the Chapter House of the Valencia Cathedral; ii) registration process by laser scanning the surface and controlling data accuracy via visible active triangulation in real-time on the computer screen; iii) photographic registration of the work with visible and infrared light, providing more information for result interpretation; iv) post-production phase focused on data processing and volume interpretation, based on two parts (a) cleaning the digital clone by eliminating noise and correcting errors in the polygonal mesh calculation, and (b) digital processing through extraction, result interpretation, and obtaining the 3D model [22,47,48] in correspondence with patterns and designs; v) 3D digital model printing and post-processing (cleaning, support removal, and surface finishing) [49].

4. Results and discussion

4.1. Digital 3D model

Fig. 3 shows the 3D digital model of the Holy Chalice before and after the optimisation process. In order to compensate for the slight variation in surface relief caused by the interaction of the laser beam projected onto each vein, a levelling treatment was applied using masks, intended to adjust the external topography and obtain a homogeneous surface texture consistent with the relic's materiality (Fig. 3b). To this end, a displacement analysis was first carried out to quantify the degree of laser absorption by the agate stone and its geometric translation in the model resulting from the 3D acquisition. This analysis revealed depth values close to 0.46 mm in the areas with the greatest absorption of the laser beam (Fig. 3c, upper). On the basis of these data, ZBrush software (Maxon®) was used. Although it is not intended for the metrological processing of data but rather for organic digital modelling, it has a strong capacity to manage high density polygon meshes, allowing precise control over the operations applied to surface levelling. Specifically, the Mask tool was used, which made it possible to select and mask, that is to say exclude from modification, specific polygonal regions that must be preserved. This tool incorporates several automatic selection algorithms adapted to different geometric typologies. In the present case, the algorithm known as Mask by Cavity was applied, enabling the isolation of only the topographic areas corresponding to the vein subject to correction by adjusting specific sensitivity parameters. The initial model, obtained after the first processing stage, comprised 1400,000 polygons (Fig. 3a). The final model, generated after the specific treatment of the relic's topography, including an increase in polygonal resolution intended to minimise the impact of the intervention, reached 2700,000 polygons (Fig. 3b). This increase in resolution is justified because a higher polygon density allows more accurate detection of topographic variations, especially at the boundaries between the areas to be preserved and those to be treated. This enables more uniform masking, which in turn allows a more subtle intervention on the surface and reduces the impact of the treatment on the initial model's precision margin.

Throughout the procedure, a copy of the original model was retained without any modification and used as a reference to carry out the necessary checks through deviation analysis in Geomagic Wrap®, in order to minimise as far as possible the effect of the treatment on the precision of the final 3D model. In this context, and given that the depth range of the cavities associated with laser absorption was known, between 0.03 and 0.46 mm (Fig. 3c), it was possible to fine tune the sensitivity of the cavity based selection algorithm. An inverse selection was then performed, resulting in a mask located exclusively in the external areas to be preserved, ensuring zero impact on them. The most depressed zones were moved up to the level of the preserved surface. After this operation, a new displacement analysis was carried out on the corrected model, and it was observed that the deviation range converged towards values close to 0.07 mm, without reaching the 0.1 mm threshold (Fig. 3c, lower right). Although the treatment implies an accumulated loss of precision, initially estimated between 0.025 and 0.035 mm attributable to the acquisition system, to which an additional margin of approximately 0.07 mm derived from the topographic correction was added, the resulting total error margin lay between 0.035 and 0.1 mm, rounded upwards. These values were considered acceptable as they fell within the error margin assumed for the present study. It should be noted that the visualisations shown in Fig. 3c use simulated artificial lighting systems typical of digital modelling environments, intended to emphasise topographic variations as a function of the virtual material applied. This visual enhancement produces models that appear more contrasted than they would under real conditions. Nevertheless, the described procedure made it possible to correct the volume in accordance with the originally recorded model, minimising the potential for subjectivity inherent in any interpretative surface treatment.

Once the process was complete, it was possible to analyse the resulting model, verify volumes, dimensions and wall thicknesses, and generate its physical reproduction (Figs. 5 to 8). The resulting 3D model file was exported in .STL (Standard Tessellation Language) and .OBJ formats, both consolidated as universal standards since the expansion of additive manufacturing in the

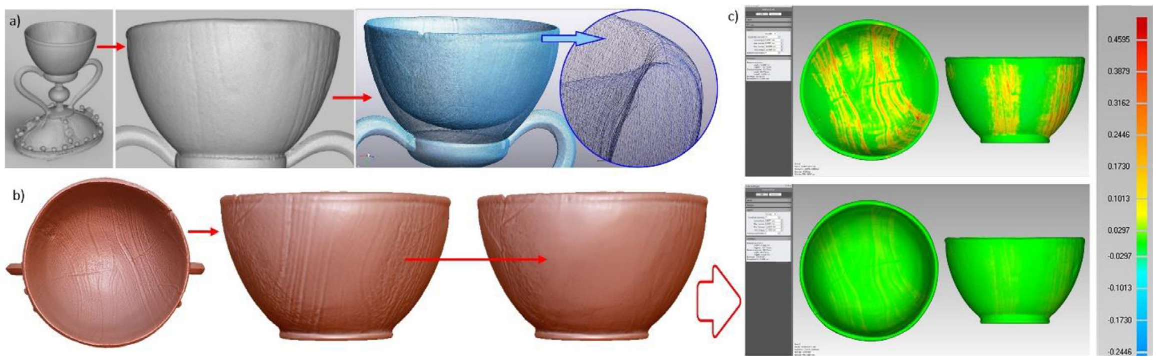

Fig. 3. (a-c). 3D digital model of the Holy Chalice. a) General and detailed 3D model and the polygonal mesh obtained b) View of the optimised chalice. A slight variation in the surface relief can be observed, corresponding to the veining of the agate. This is due to the higher transmission of the laser light, which is proportional to the translucency of each vein (the clearer the veins, the lighter passes through them, resulting in a more sunken relief). The final model with the topographical correction according to data from the Geomagic Wrap® software. c) Topography displacement analysis: registered model (top), corrected model (bottom), displacement scale (right).

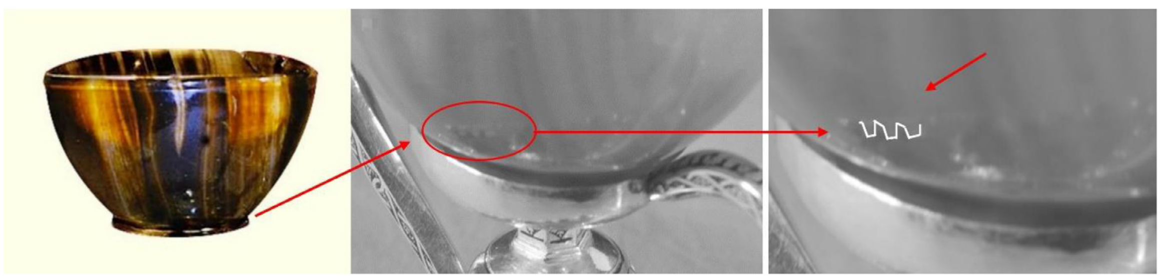

Fig. 4. Relic under investigation without the attributes of stem and base (image courtesy of the Valencia Cathedral Archive). Infrared photograph showing the cup crimped to the metal structure and detail of the previous image showing the crenellated edges of the crimp or rim, composed of a series of projections and depressions.

1980s. Their use ensures compatibility and long term preservation of the digital model. Given the relic's historical and symbolic relevance, as well as its status as property of the Cathedral Chapter of Valencia, unrestricted public dissemination of the complete digital model was not considered appropriate in order to ensure non-commercialisation and strictly scientific use. Nevertheless, the data management strategy follows FAIR-oriented principles regarding long-term preservation, traceability, metadata documentation and controlled scientific access for research purposes. In this way, the model remains deposited within the research team's holdings as a basis for future collaborative studies with competent institutions.

Detailed analysis of the 3D model of the goblet has revealed the existence of a specific crimping system on the goldsmith's stem that holds the goblet together as a whole (Fig. 4). The infrared-light image shows a goldsmith's work using the crenellated or tapering-edge assembly system composed of flanges and recesses distributed in a line. This method of joining has its parallel or resemblance in the chequered or "taqueado jaqués" mouldings, a mediaeval decoration widely used in Romanesque art originating from Jaca (Huesca), and which would confirm its presence in the monastery of Juan de la Peña between the 12th and 14th centuries, as various studies point out [1,2,9,50]. It is a very sophisticated joining system for the time and is efficient thanks to its adaptability to curved geometric shapes. In addition, this system improves the connection of the cup to the stem, given the irregularity of the discoid base, giving it a firm grip and fit. Once the base of the cup is pressed onto the stem, the flanges adapt to the lip in a continuous row, preventing them from separating (Fig. 4). In cups of the period, it was common for the base disc to provide stability when placed on a horizontal surface. This, with a slightly curved and flat disc shape, has a proportional size that ensures sufficient balance and strength in terms of stability and functionality to maintain the cup's poise without swaying.

4.2. Dimensional features evaluation

The 3D model has provided precise measurements and an accurate representation of the cup. These dimensional characteristics make it possible to support parallels and correspondences with other cup types and to establish a more approximate dating. Fig. 5 shows various profiles of the relic with the most accurate metric data to date. There is some dimensional variability in terms of overall size and wall thickness. Dividing the cup into four parts and/or profiles results in an overall diameter of between 96.44 and 97.85 mm; a maximum wall thickness of 8.28 mm and a minimum of 1.91 mm; and an internal cup height of between 51.17 mm and 51.46 mm. The maximum variation in cup thickness is found at 32.66 mm from the rim, section AC. These variations in thickness and the presence of irregularities are indicative of mechanical-manual and artisanal processing. Overall, the dimensional study provides information on the design, manufacture and use (volume capacity) of the relic, as well as contributing to a better understanding of the history and nature of this revered relic.

An instance found in the Getty Museum, an agate cup (ref. 72.AI.38) dated 300–100 BC, with a size and thickness (± 3.45 mm), confirms the similarity to the piece under study here and possibly to the cups of the period. Another piece, recently auctioned [51], falls within a comparable dimensional range and exhibits a similar overall profile to the relic. Inspired by Hellenistic agate bowl productions, it is a rare Roman agate murrine dated to the 1st century BC [13,52]. This data could suggest the existence of models (designs or patterns) that correspond to those developed in a particular period in constant evolution. As is evident, the thickness is variable in different parts, depending on the shape and overall design of the piece, with the upper rim of the cup being thinner than the bottom or the side walls. The plausible coincidence of measurements and shapes, and the technique of polishing

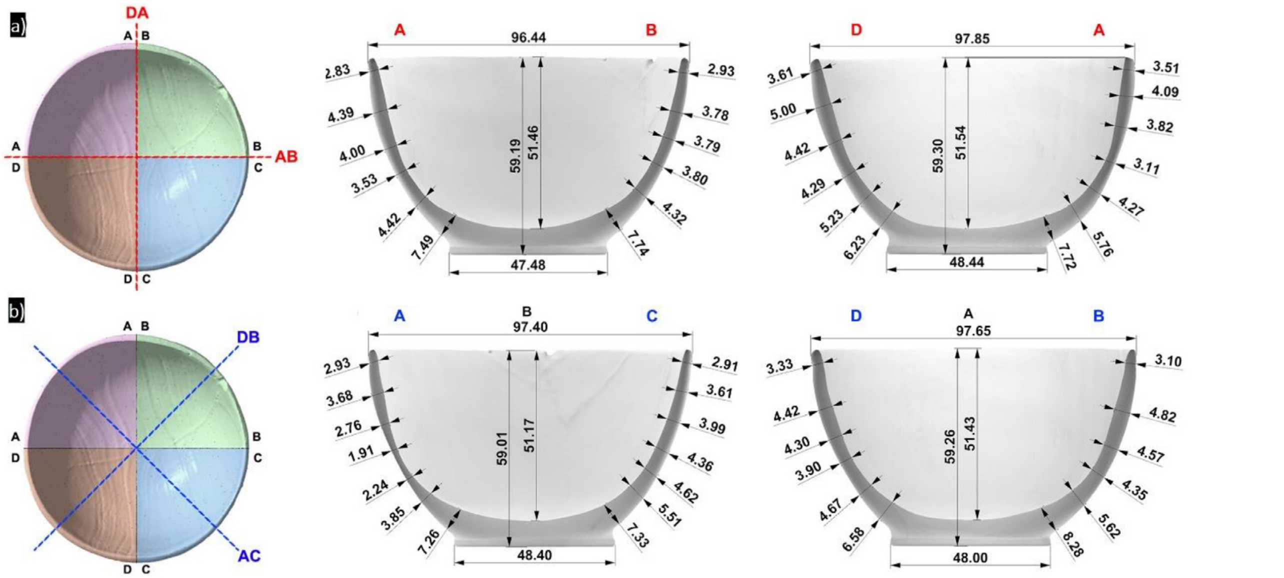

Fig. 5. (a-b). Metric data of the relic. a) zenith view of cuts AB and DA; cut section AB, and cut section DA. b) zenith view of cuts AC and DB; cut section AC and cut section DB.

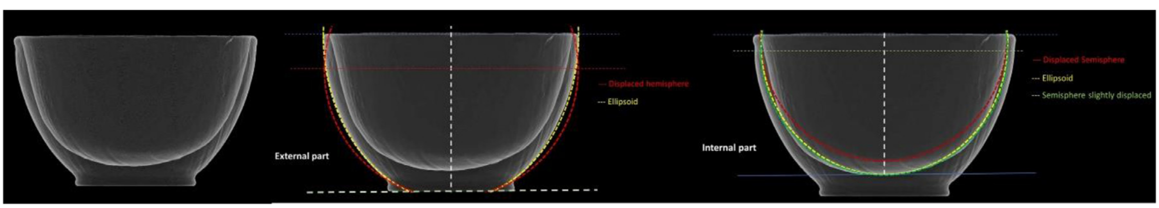

Fig. 6. General view 3D model of the agate cup. Overlapping shapes on its external and internal face.

the objects in a uniform and skilful manner, allow us to demonstrate reliable and significant data for the dating and categorisation of the goblet.

Therefore, the data on the size and wall thickness of the cup have provided valuable information that complements the physical and material characteristics of the relic to date.

4.3. Cup shape

Fig. 6 shows graphical information on the shape of the cup from the resulting 3D digital model. The digital treatment of the relic has made it possible to know exactly the deformations and the variability in the thickness of the walls that define an ellipsoidal shape, both on the outer and inner sides. In this sense, if the 3D model is carefully analysed in rotation or on a turntable, the shape corresponds perfectly to a spheroid. Undoubtedly, the original geometric shape would be a hemisphere that was deformed by the manual work on the stone, resulting in an ellipsoid of revolution or a hemisphere slightly displaced from the central axis. This detail suggests that the vessel was carved alternately, adjusting the shape of the outer surface and gradually hollowing out the interior by trepanation/abrasion/revolution.

Likewise, the archaeological drawing of the relic has been represented for the first time (Fig. 7) in accordance with the standards for the representation of archaeological pieces [53–55]. It provides a reference document for study and comparison with other pieces of closely similar characteristics and production period. This work is the starting point for the development of the 3D acquisition of other pieces from institutions and public-private entities that provide verifiable data on this typology of pieces.

4.4. Volume of the agate cup

The 3D digital model made it possible to calculate the area and volume of the relic (Fig. 8a). The area was 67.15 mm^2 and the volume 235 ml. These results were additionally supported by a 1:1 printed copy derived from the digital model, used as a handling surrogate under the access constraints of the study. The 3D printed model enables analysis without manipulating the original object, facilitating research into materials, manufacture, and possible symbolism associated with the cup's design.

In this sense, the main function of this type of piece was to contain wine during festive and/or religious events. It is therefore extremely important to know the amount of liquid that could be contained in the goblet. The analysis of the model has made it possible to detail the area and volume of the goblet, allowing a gradual understanding of its full capacity (Fig. 8b). If it is assumed that this cup could have been used during the Eucharist or the Last Supper, it should hold at least one reviit (equivalent to 73 ml, 86 ml, 150 ml or 161 ml according to various rabbinical sources) [56] or several reviits of smaller capacity, leaving a margin of approximately 1 cm below the rim. These measurements are essential for researchers studying such artefacts and present new challenges for understanding historical practices and their religious implications. Furthermore, variations in cup capacity according to rabbinic interpretations suggest a diversity of associated rituals, opening the way for further exploration of the relationship between liturgy and material design in ancient religious contexts. Furthermore, the tolerance in the capacity of the cup suggests the possibility of practical or symbolic adaptations according to different communities or specific rituals, highlighting the richness and

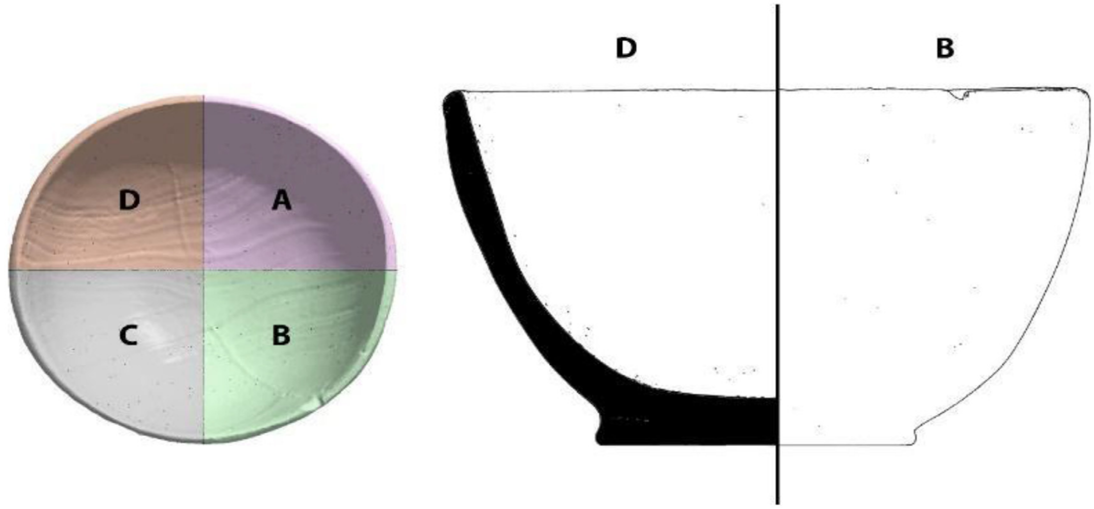

Fig. 7. Chalice from Valencia Cathedral. Zenithal view dividing the piece into four quadrants and, Archaeological drawing (profile view D-B).

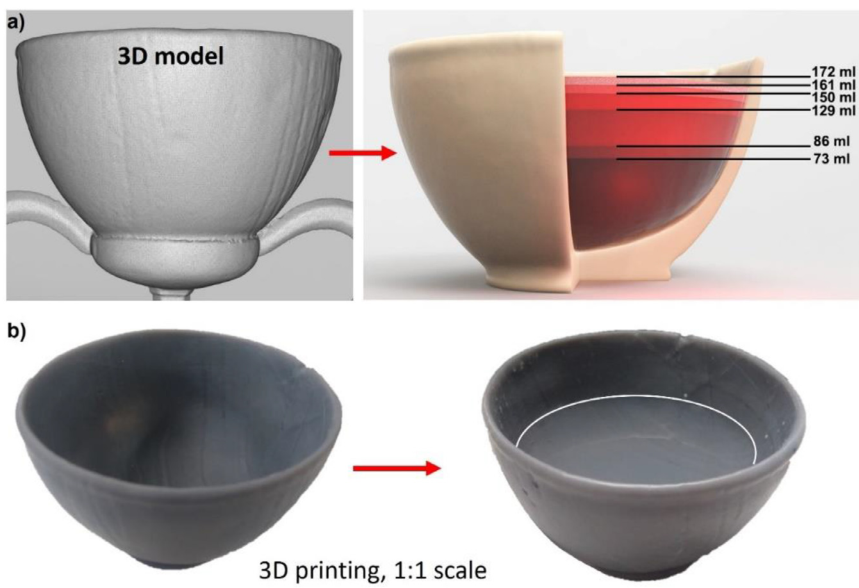

Fig. 8. (a-b). Determination of the volume of the relic: 3D model and representation of the total capacity of the 3D model at different volume levels; b) Hard copy printed at a scale of 1:1 from the digital model and volume occupied by the liquid at a quantity of 86 ml (water), scale simulating the filling of the relic.

complexity of ceremonial practices in antiquity. Finally, the analysis of the cup from a volumetric perspective can shed light on the symbolic importance of the act of filling and emptying in ritual contexts, thus deepening our understanding of the relationship between form, function and meaning in ancient religious objects.

4.5. Glyptic

Despite the fact that in recent decades several studies have been carried out on the cup of the Holy Chalice, providing data on its history, iconology, symbolism and even typology, there are still certain unresolved questions about how this type of stone vessel was carved. Since antiquity, human communities have identified and utilised naturally available materials, such as stone, wood, and metal, transforming them through increasingly specialised techniques. These resources were employed to produce objects intended for both utilitarian and symbolic purposes, embedding within them the cultural, technological, and aesthetic values characteristic of each historical period. In the specific case of carved and hollowed stone cups, their production attained a remarkable level of sophistication, owing to a continuous technical tradition attested since the third millennium BC in the craft sectors of ancient Egypt, Mesopotamia, Persia, and various East Asian regions [57–62]. The mastery of these techniques rested with artisans highly skilled in hard stone carving. This craft, perpetuated through successive generations, entailed rigorous expertise in material selection and systematic planning, both indispensable for converting raw stone into objects of exceptional refinement. In this regard, experimental archaeology, pioneered and brought to its highest level by Denys Allen Stocks, has provided compelling evidence of how ancient civilizations mastered the working of diverse materials. Particularly noteworthy is the carving of stone using metal, hybrid (wood and metal or wood and stone), and composite (wood, metal, and stone) tools, operated through rotational motion to achieve precise and efficient cutting [16,17]. The craftsmen and/or artisans were organised by trades and these were carried out in families, generally inheriting the tools and techniques from father to son. Among the tools for drilling, carving and finishing vessels, which were used until well into the 1st century AD, there was a great variety; there were different types of trephines, in the form of a wooden stick with a forked tip that housed a rotating stone, or circular metal tubes; also smooth or serrated saws,

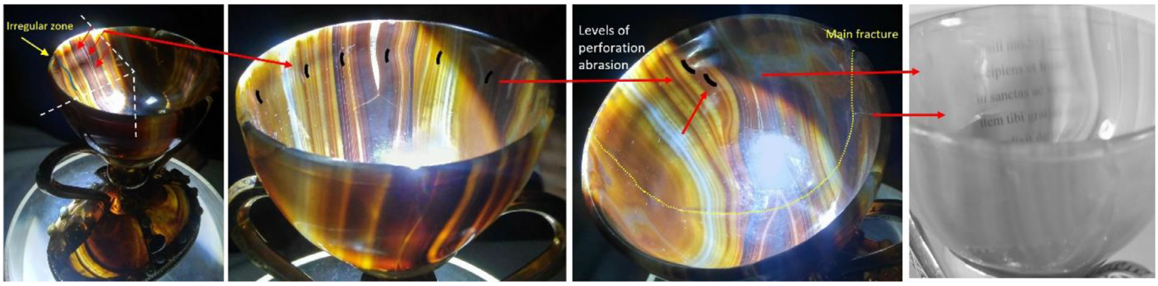

Fig. 9. General and detail view of the cup of the Holy Chalice. The irregularity of the surface of the inner face can be seen along the entire body and mouth of the Chalice, and the marks of the turning lathe for the refining of the walls after the perforation or trepanning stage at different levels of depth can be seen. Infrared photograph showing the translucency of the cup, showing a written Latin text, similar to the glass cups that rivalled them in transparency, wall thickness and colour.

small metal rods with points (copper, bronze and iron) and emery edges; even the use of the violin-bow lathe as a revolutionary tool for smoothing surfaces, as can be seen on the chalice cup (Fig. 9). Similarly, the existence of models, stencils and/or drawings with the design of the vessels and approximate pre-established measurements would most likely have circulated among craftsmen and in workshops, although no data on this have come to light. However, the presence of formally similar pieces suggests a pattern of design and measurements that was widely disseminated over the centuries and the different imperial dynasties that succeeded one another [5,11,12].

On the other hand, the petrological properties of the different natural stone materials formed by minerals are also aspects to be considered [60,63,64]. In this sense, hardness, density, mechanical strength and interstitial water are the properties responsible for a better or worse response in the workability of the stone. The specific case of the Chalice, a banded quartz agate with a hardness of around 7 on the Mohs scale and a conchoidal fracture, must have required a great deal of effort and technical skill to be worked with the ancient tools mentioned. According to the data collected in the 3D register, the relic shows obvious deviations in the annular area of its base and in the groove of the mouth, typical of handicraft work. Likewise, the inner surface of the vessel shows greater morphological irregularities than the outer surface, where it is quite heterogeneous along the entire body of the chalice; these irregularities are evident in the thickness of the walls and in the signs or marks of rotation shown in Fig. 9. Despite these deformations, the result of the carving is imperceptible to the human eye due to the banding and polishing of the piece, with the intention of imitating contemporary glass goblets [12,65].

Conclusions

The application of 3D registration and printing technologies to the Holy Chalice of the Valencia Cathedral has significantly contributed to its analysis and understanding. The key findings of this study can be summarised as follows: i) High-Precision 3D Modelling: The use of the MetraScan3D laser scanner has enabled the creation of a high resolution 3D digital model of the Holy Chalice suitable for metrological and morphological analysis within the error margin discussed in the manuscript. This non-destructive approach supported real time monitoring and allowed detailed assessment of surface topography without physical manipulation of the relic. In addition, an archaeological drawing of the relic is presented digitally for the first time. ii) Accurate Measurements: The study determined the exact dimensions of the agate chalice, taking its heterogeneity into account, with an internal height of 51.17 to 51.46 mm, a diameter at the top of the cup ranging from 96.44 to 97.85 mm, and wall thicknesses between 8.28 mm and 1.91 mm (with a ± 0.1 mm margin of error according to the post-production data). These precise measurements, made possible by the 3D modelling technique, are particularly important for future conservation and historical analysis. iii) Morphological Analysis: The superimposition of geometric shapes on the concave and convex zones of the Chalice revealed that its form is a slightly ellipsoidal hemisphere, with the ellipsoid truncated by the base. This detailed analysis provides new insights into its craftsmanship and construction. iv) Volume Capacity: The exact liquid volume capacity of the Chalice was calculated to be 235 ml, offering valuable information for interpreting its potential liturgical use. v) Artisanal Craftsmanship: The study highlights the exceptional skill of ancient artisans who crafted this object from banded agate, a material known for its hardness and difficulty to work with due to its microcrystalline quartz structure and characteristic conchoidal fracture. The presence of irregularities on both the internal and external surfaces of the cup suggests the use of manual perforation tools, lubricated with water and abrasive particles, along with abrasive revolution tools like the bow lathe. The study further indicates the likely use of templates or models to guide the craftsmanship, evidenced by the Chalice's similarity to other stone vessels of the period. This deepens our understanding of ancient Mediterranean and Eastern artisans and their pragmatic approach to stone carving. vi) Implications for Future Research and Conservation: This study opens the door for further research on the Chalice and similar artefacts. The detailed findings provide a foundation for developing best practices for the conservation of objects made from complex materials such as agate, gold, and precious stones. Specific environmental conditions are recommended to ensure the long-term preservation of the Chalice, with guidelines that can be applied to other relics of similar typology.

Beyond the individual techniques employed, the study demonstrates the importance of integrating acquisition, metrological analysis, surface interpretation, volumetric evaluation and physical reproduction within a coherent methodological pipeline adapted to the specific constraints of complex heritage artefacts. The effectiveness of the workflow lies not only in the precision of each individual operation, but in the way these processes interact to generate reliable scientific information while minimising intervention on the original object.

Broader impact

The research has broader implications that extend beyond the academic and conservation communities. The creation of a highly detailed 3D model not only preserves the Chalice digitally but also ensures that it can be used for future restoration efforts, should the original be damaged. This digital model can also be employed for public engagement, providing virtual exhibitions that make the Chalice accessible to a global audience. It offers opportunities for educational initiatives, creating interactive learning tools in museums and online platforms, allowing the general public to engage with the Chalice's history in innovative ways.

The study also underscores the importance of interdisciplinary collaboration in cultural heritage preservation, demonstrating how advanced technology can enhance the understanding of historical artefacts. By contributing to international digital repositories, this research helps preserve and study religious relics on a global scale, ensuring that cultural treasures like the Holy Chalice are protected for future generations.

Finally, the study advances technological applications in the field of cultural heritage preservation, setting a precedent for the use of 3D scanning technology in analysing challenging materials, like those found in the Holy Chalice. It paves the way for future innovations, particularly in the non-invasive study and conservation of significant historical artefacts.

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