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Virtual Anastilosis of a Baroque Dome Disassembled Two Decades Ago: The Case of the Presbytery of Valencia Cathedral.

This study presents the virtual anastilosis of the Baroque dome in the presbytery of Valencia Cathedral, a significant architectural piece demolished two decades ago to reveal Renaissance frescoes.
Employing a novel integration of multi-temporal laser scanning data, the research reconstructs the dome's previous state, showcasing the potential of digital techniques in preserving architectural heritage. Initially, the dome was digitally documented before its removal in 2005, following the discovery of frescoes by Paolo de San Leocadio and Francesco Pagano, hidden behind of it.
This documentation utilized phase difference laser scanning, a method that captured the dome's geometry with high precision. Recently, further scanning of the cathedral's main chapel was conducted, providing a detailed current state against which the previous model could be aligned and integrated.
The methodology involved evaluating and optimizing both sets of data to accurately position the digitally reconstructed Baroque vault within its original context, overcoming challenges such as the absence of normal information in earlier scans.
The result is a high-fidelity 3D model of the cathedral's main chapel, with the Baroque vault accurately reinstated, illustrating the harmony between Baroque and Renaissance elements that was disrupted by the dome's demolition.
This project highlights the critical role of digitized surveying and 3D modelling in architectural heritage preservation, offering insights into the importance of maintaining a digital archive for heritage sites, allowing for virtual reconstructions that honor their historical integrity and complexity.

Keywords:
Architectural survey; virtual anastilosis; digital reconstruction; heritage preservation; Cathedral of Valencia

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1. INTRODUCTION

Proposing an anastylosis intervention in architectural heritage that is partially destroyed or disappeared always brings with it a theoretical debate on concepts such as authenticity and integrity (Mancini et al., 2021). Anastylosis, which involves the re-erection of structures from their original elements, raises questions about the extent to which it is possible or desirable to restore a building to its original state. This process involves technical and ethical challenges, as it requires balancing the need to preserve historical materiality with the possibility of interpreting and reconstructing elements that may have been lost or damaged.

However, in the digital age, an innovative alternative has emerged: virtual anastylosis. This approach involves the digitized survey of existing structures to digitally recreate historical structures without physically intervening in the original remains (Cardillo, 2015). Virtual anastylosis offers a way to address the same technical and ethical challenges, but from a perspective that minimizes the risk of damaging material heritage (Adembri et al., 2018).

Our study model, the Valencia Cathedral, dates to the 13th century. It is located in an area of great urban antiquity, partly on the site of the Forum of Valentia, dating from the 2nd century BC. Part of the current building also sits on what was the Visigothic Basilica-Cathedral in honor of Saint Vincent Martyr, deacon of Zaragoza and patron of Valencia. It is a monument of unquestionable historical and artistic importance, widely studied from academic and scientific perspectives. It is worth noting at this point the studies on its layout conducted by Navarro Fajardo (2003, 2006) and more recently, using digital models, by López González et al. (2023).

Some authors establish three major phases in terms of its architecture over its nearly eight centuries of existence (Benito Goerlich, 2010). The first corresponds to its medieval stage and its elegant late Gothic culmination (Zaragozá Catalán, 2000). Subsequently, and following occasional Renaissance interventions, a process of progressive Baroquization began, which was completed with the splendid classical renovation of the last quarter of the 18th century. The third phase, following a disastrous fire and looting during the last of the Spanish civil wars, involved a prolonged intervention during the central decades of the past century with the aim of Gothic restoration but resulted in the creation of a cathedral that had never existed before (Chiner Vives & Simó Cantos, 1983). Joaquín Bérchez (2016) describes it as “the most monumental multiple palimpsest of Spanish architecture”.

One of the most critical episodes of this last phase of restoration fervor occurred in the mid-2000s. In June 2004, during the comprehensive restoration efforts undertaken on the Baroque altarpiece in the presbytery of Valencia Cathedral, an archaeological discovery would transform the understanding of its architectural history. The removal of the Baroque dome that crowned the Main Altar unveiled Renaissance frescoes hidden over the webbing of the Gothic vault of the apse (Vila Ferrer, 2007). These frescoes, attributed to the Italian masters Paolo de San Leocadio and Francesco Pagano, date from between 1472 and 1481, add-

Fig. 1 - Photomontage of the state before (left) and the state after (right) the intervention to dismantle the baroque vault.

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ing an unexpected chapter to the cathedral's rich narrative.

However, admiration for this discovery was soon overshadowed by controversy. The decision to demolish the Baroque dome, which protected these artistic treasures, made in 2005, sparked debates over architectural heritage preservation and the tension between artistic styles (Juan Vidal, 2007). The dome, an integral part of the remodelling in the Valencian Baroque style signed by architect Juan Pérez Castiel, was sacrificed to reveal the Renaissance frescoes, raising questions about the balance between conservation and display (Figure 1).

Indeed, the intervention did not aim to restore the vault to its Renaissance state—a feat that was complicated, if not impossible. Rather, the true intention was to showcase the valuable frescoes and enhance their value. Therefore, the decision was made to remove, in addition to the Baroque brick webbing, the majestic hanging keystone, as it would draw too much attention away from the brilliant frescoes. However, the decision was made to preserve the ornamentation covering the genuinely Gothic ribs, as well as the window tempiettos.

Before the demolition, a pioneering digitalization effort was undertaken using phase difference laser scanning technology, led by Professor Lerma's team, employing the Faro LS880 scanner (Lerma García et al., 2006). These scanning files, in XYZ format, became virtual witnesses of the Baroque dome before its physical disappearance. Years later, these scanning files were donated to continue the research, marking the beginning of an ambitious project. By integrating laser scanning data from two different periods, the research aims to virtually reconstruct the state prior to the demolition of the Baroque dome in the presbytery of Valencia Cathedral. This innovative approach of "virtual anastylosis" seeks to create a digital synthesis that recreates the disassembled Baroque vault two decades ago.

2. OBJECTIVES

The overarching aim of this piece of work is to virtually reconstruct the Baroque dome in the presbytery of Valencia Cathedral, utilizing advanced digital technologies. This endeavor seeks not only to revive a piece of lost heritage but also to underscore the critical role of digital documentation in the preservation of architectural monuments. Through this initiative, the gap between past and present architectural states is bridged, thus contributing to the broader field of cultural heritage conservation (Pàmies et al., 2023). The objectives of this piece of work outline its scope and ambitions:

-Modeling of the Presbytery: The goal is to virtually reconstruct the presbytery's state prior to the dismantling of its Baroque dome. This task will utilize laser scanning technologies and 3D modeling to accurately capture the architectural features of the presbytery as they originally stood, ensuring a faithful digital representation of this historically significant structure.

-Virtual Anastilosis: The research aims to perform a virtual anastilosis of the lost Baroque vault by integrating two sets of laser scanner data. This process explores the potential for digital recovery and reconstruction using information gathered nearly two decades apart, demonstrating the evolving capabilities of digital technology in heritage preservation.

-Recovery of Historical Information: This objective focuses on retrieving 3D scanning information from an earlier era, ensuring its proper adaptation and integration with more contemporary digital models. It underscores the importance of fidelity and coherence in the digital representation of the Baroque vault, utilizing data collected at different times to achieve a seamless reconstruction.

-Demonstration of the Importance of Digital Documentation: This piece of work aims to demonstrate the significance of documenting architectural heritage via digital surveying techniques. By employing the most innovative methods available at each respective time, the vital role of digital preservation in understanding and conserving cultural heritage is highlighted.

-Contribution to Knowledge: The initiative contributes to the knowledge and application of digital restoration as a fundamental tool in the preservation of architectural heritage. By providing an exemplary case study, the capacity of technology to reconstruct and understand architectural elements that have been lost over time is showcased, thereby offering new perspectives on historical architecture and its preservation.

3. METHODOLOGY

The methodology employed aims at the virtual anastilosis of the Baroque vault. The workflow begins with the review and evaluation of scanning files provided by Professor Lerma. These

Fig. 2 - . Digital model of the current state of the Presbitery

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documents, in XYZ format, store the scanning information as an extensive matrix with the spatial coordinates of each point. However, this file type lacks normal information, posing a challenge in generating a triangulated mesh.

On the other hand, the current state of the main chapel (not just the vault) of the cathedral has been documented using laser scanning (FARO Focus3D 130) and photogrammetry (Lerma et al., 2013), from which a comprehensive digital model, geometrically optimized and with real materials, has been created (Figure 2). Being more recent, this digital survey and the resulting digital model offer greater detail than the preceding survey.
After optimizing both digital models, the model of the missing Baroque parts can be placed in its original position, using common features in both models as reference points for alignment. These features include the Baroque lunettes and the ornamental detailing of the ribs.

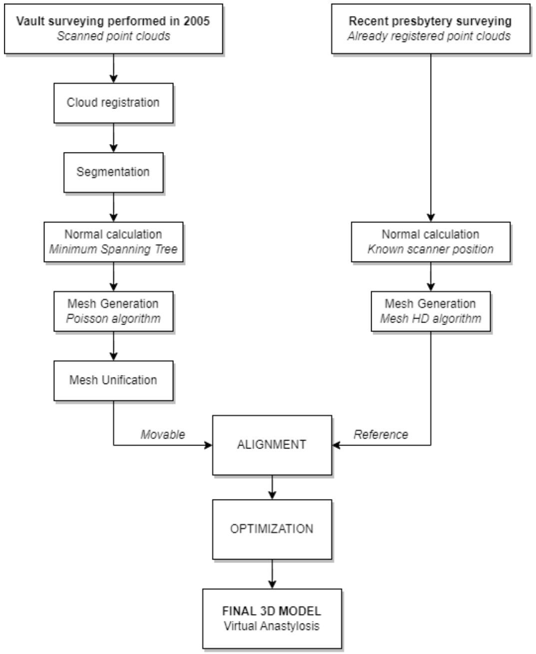

Fig. 3 - . Pipeline of the workflow for the Virtual Anastylosis of the Baroque vault

PREPARATION OF THE BAROQUE VAULT MESH

The preparation of the polygonal mesh of the Baroque vault involves several critical steps, starting with the registration of the various XYZ files provided by Professor Lerma into a single Baroque vault. This step is pivotal to ensure the model's cohesion and to facilitate subsequent process stages. A meticulous review of the point cloud alignment is conducted, identifying and correcting any misalignments through global and fine alignment. This adjustment allows for the movement of all clouds across five successive iterations, significantly optimizing their registration. Following this, the aligned point clouds are merged, with overlapping regions removed to avoid complications during triangulation.

Attention is given to the point cloud cleaning, where extraneous elements resulting from the scanning process, such as scaffolding structures used in prior restoration project works, are removed. This stage is crucial for purifying the model from elements unrelated to the vault, thus ensuring the model's accuracy and integrity.

The vault is then segmented into six sectors, corresponding to the vault's six ridges or crests. This procedure aims to simplify the calculation of normals, thereby facilitating the manipulation and detailed analysis of each segment. The data is exported in PLY format, chosen for its efficiency in handling binary files, significantly streamlining the workflow. These files are subsequently imported into Cloud Compare (Girardeau-Montaut, 2022), where the segments are triangulated using the Poisson algorithm (Kazhdan et al., 2006).

The calculation of normals is a critical step in this process, given its significance for surface reconstruction from point clouds. A preferred orientation of the normals following de Z axe downwards (i.e. -z) is chosen after evaluating various techniques. This orientation is implemented to distinctly differentiate between the visible and hidden faces of the points, providing a solid foundation for reconstruction.

To coherently reorient normals, the tool available in Cloud Compare under 'Edit → Normals → Orient normals → with Minimum Spanning Tree' is utilized. This method relies on the normal orientation propagation from one point to its neighbors using a minimum spanning tree, requiring the definition of the maximum number of connections per node. The correct orientation of normals is vital for the success of the Poisson algorithm, as it depends on them to accurately define the direction and shape of surfaces in three-dimensional space.

The implementation of the Poisson algorithm, with specific parameters (10, 1.00, 8, 4.00, Free),

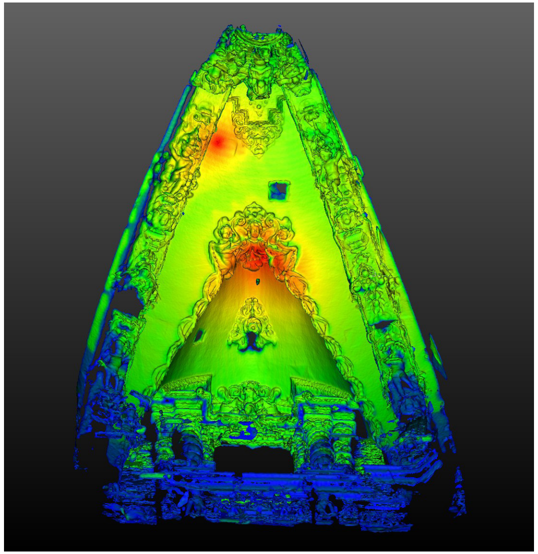

Fig. 4 - . The reconstructed surface of one of the segments of the vault

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facilitates the desired surface reconstruction. This mathematical approach is based on harmonic function theory and the energy minimization principle to solve Poisson equations that model the surface's interaction with the normal vector field. The outcome is the generation of isosurfaces from the implicit function, revealing the reconstructed geometry of the vault (Figure 4).

This method proves particularly effective for working with point clouds that may exhibit noise or incompleteness, allowing for the generation of smooth and detailed surfaces. Its application is not limited to the three-dimensional model reconstruction for visualization but also extends to scanned data analysis and other areas related to three-dimensional geometry representation.

PREPARATION OF THE VAULT'S CURRENT STATE MESH

In the preparation phase of the polygonal mesh for the vault's current state, it is crucial to meticulously extract the specific section of the point cloud corresponding to this element. The point cloud obtained via the FARO/Scene system lacked normal information. However, in this case, obtaining this information is easier and quicker than for the Baroque vault scan provided by Professor Lerma. Knowing the scanner's relative position to the point cloud allows for simpler computation of the normals. To achieve this, the file must be imported from SCENE in E57 format (which preserves the scanner's position), and when computing the normals, the method that considers the position of the Terrestrial Laser Scanner (TLS) should be selected. This approach quickly enables the program to calculate the normals for all points in the cloud.

Once the normals are calculated and depending on the need to clean the noise present in the point cloud, triangulation of the cloud is proceeded to obtain the desired polygonal mesh. This triangulation can be carried out using the Poisson algorithm, as done in the previous section, or by opting for Geomagic Design X software, which features its own Mesh HD triangulation algorithm. Both alternatives provide satisfactory results; however, the Poisson algorithm is noted for its rapid calculation speed, while Mesh HD is distinguished by its precision.

ALIGNMENT OF THE TWO MESHES

Aligning the meshes of the Baroque vault and the current state of the cathedral presents a unique challenge in the digital reconstruction process, due to the geometric differences between the two architectural states. The goal is to make the necessary adjustments—translations and rotations—to the mesh of the Baroque vault to achieve its precise alignment with the mesh of the current structure. This process starts with a manual alignment, placing the Baroque vault as close as possible to its expected final position.

When registering point clouds of the same architectural object, it is assumed that points from the different clouds define surfaces existing within that object, prompting the system to iteratively search for the best way to fit the clouds together until the error is below a predetermined threshold or the specified number of iterations is completed. However, this procedure gains additional complexity when faced with two digital models that, representing two historical phases of the same space, describe geometrically distinct states. The presence of matching elements, such as lunettes and ribs, provides an anchor point for alignment but requires a detailed approach for its correct implementation. The selective removal of non-matching components, particularly the Gothic webbing in the model of the current state, becomes a necessary step to focus the alignment on the coinciding common elements.

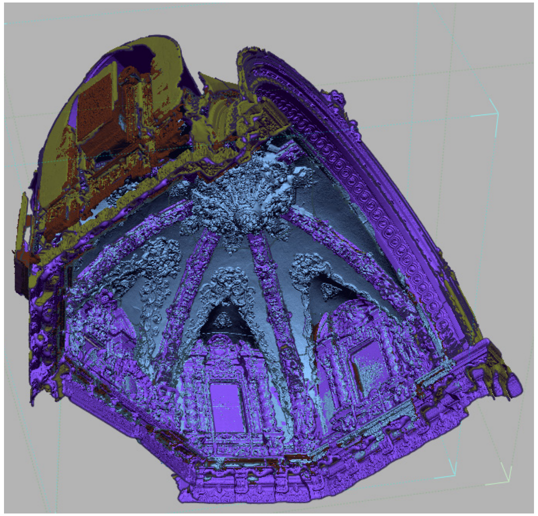
Once this foundation is established, fine-tuning of the alignment proceeds, with the vault of the current state kept fixed and adjustments made to the Baroque vault. The successful completion of this stage allows for the removal of duplicated or coinciding parts of the Baroque vault, replacing them with the corresponding parts from the current model, which presumably are more accurate (Figure 5). The merge tool in Geomagic Design X facilitates the unification of all vault fragments, resulting in an optimal representation of the Baroque vault with the best possible geometry.

MESH OPTIMIZATION

Optimizing the polygonal mesh is a crucial step in the digital restoration process of the Baroque vault and lunettes, following the successful reconstruction of their geometry in high definition. This procedure, essential for the refinement and enhancement of the digital model, is carried out following a meticulous approach that ensures both aesthetic fidelity and computational resource efficiency of the model.

Initially, a semantic segmentation of the ornamental and architectural elements that make up

Fig. 5 - . Integration of both meshes: Baroque vault in blue, current state vault in purple



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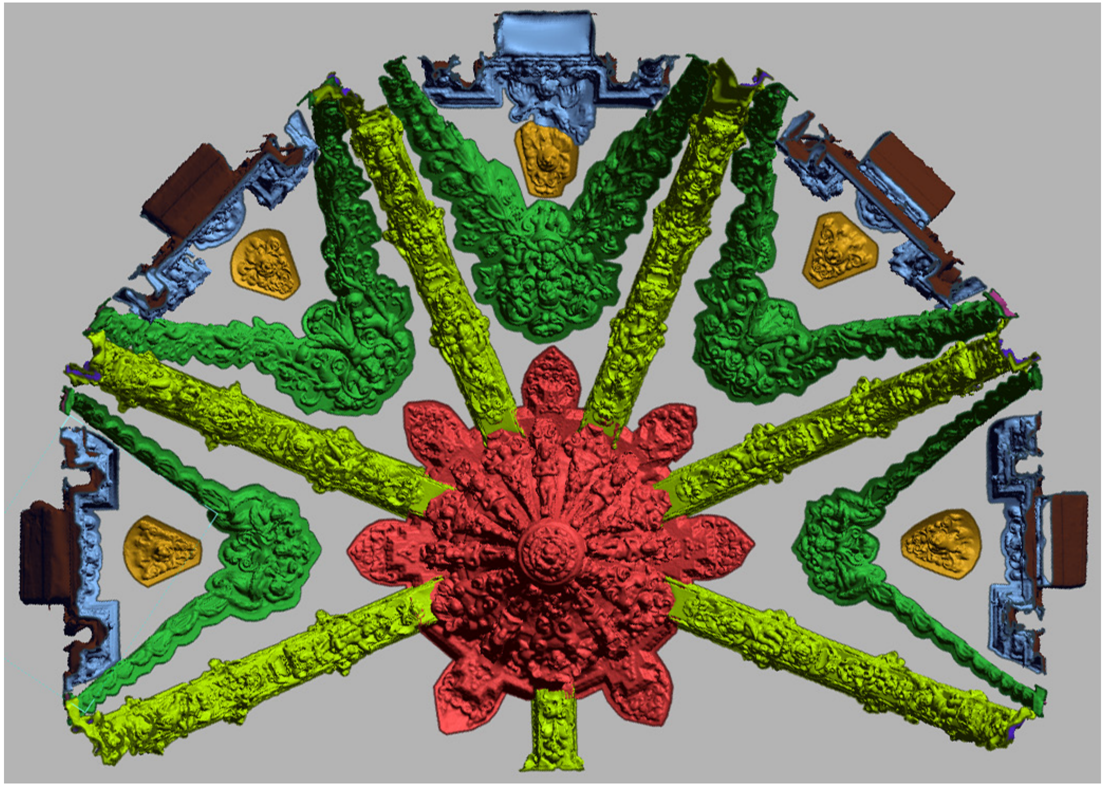
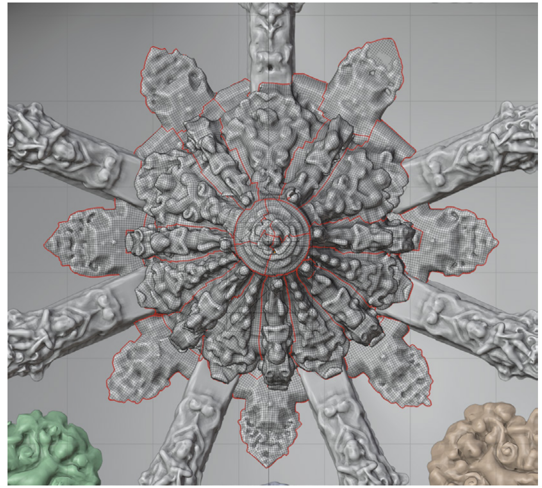


Fig. 6 - . Ornamental classification before being geometrically optimized

Fig. 7 - . Automatically retopologized model of the Baroque keystone with seams (in red) to UV parametrize



the vault is performed (Fantini & Cipriani, 2018) (Figure 6). This process not only facilitates detailed manipulation of each segment but also sets the stage for more focused intervention in polygon reduction, a task approached through advanced retopology techniques.

Aware of the importance of optimizing the model without compromising its visual or historical integrity, the possibilities offered by automated retopology systems are explored. This exploration reflects a commitment to efficiency and precision, seeking to minimize computational load without sacrificing the detail richness that characterizes the model. Each model fragment, once segmented, is exported in PLY format for processing in Instant Meshes software (Jakob et al., 2015), where optimization optimally balances geometric fidelity with polygonal efficiency (Alessandro Merlo et al., 2013). The optimized models are subsequently exported in OBJ format for further manipulation.

The importation of these models into our 3D modeling program marks the next phase of the process, where potential imperfections in the low poly model generated almost automatically by Instant Meshes are adjusted. This adjustment also lays the groundwork for the application of UV mapping techniques, an essential step for the correct texturization of the model. Defining seams in the low poly model allows for efficient unwrapping, facilitating the generation of normal maps through the texture baking process (Figure 7).

With the UV mapping completed, the creation of detailed textures that visually enrich the model proceeds. The application of a golden material to the ornamental elements, enhanced by the generated normal maps, lends the model outstanding authenticity and realism. For the components of the webbing, a white plaster material is chosen, which contrasts with and effectively complements the golden ornamental richness.

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4. RESULTS:

The primary outcome of this work is the generation of a high-precision, geometrically accurate, and photorealistic 3D digital model of the main chapel of Valencia Cathedral, integrating the demolished Baroque vault in its original position (Figure 8). Consequently, it becomes possible to virtually reconstruct a Baroque architectural space, stylistically harmonious, which was marred by the controversial decision to reveal the fabulous Renaissance frescoes.

5. CONCLUSIONS

The Valencia Cathedral, with its intricate blend of architectural styles and periods, has provided an exemplary framework to assess the effectiveness of digital surveying and modeling techniques in architectural heritage recovery. The project's virtual repristination of the Baroque vault in the presbytery has not only showcased the potential for digital techniques to produce accurate and richly detailed virtual reconstructions but also opened new avenues for exploring historical and aesthetic elements that were previously inaccessible or lost.

This case study strongly highlights the crucial role of graphic documentation in preserving architectural heritage, presenting digitized metric surveys as indispensable tools in protecting the various evolutionary phases of such elements. The endeavor reinforces the assertion that digital documentation is not merely beneficial but essential for interventions in architectural heritage or any unforeseen alterations to its integrity.

The indispensability of maintaining detailed digital records is underscored, serving as a defense against irreversible loss. The capability for virtual anastilosis—recreating the original geometry of architectural components digitally—emphasizes the importance of graphic documentation for the virtual restoration of heritage. This methodology

Fig. 8 - . Final result: integration of the barroque dome on its original location

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Fig. 9 - . Comparison of both digital models: current state (left) and baroque vault (right)

Fig. 10 - . Cross section showing the overlapping of vaults

ensures the feasibility of virtually reintegrating the original essence and form of structures that have experienced changes or deterioration over time.

Regarding the future research, the digital model developed through this project can be published and disseminated through advanced platforms such as augmented reality (AR) tools, virtual reality (VR) environments, and video game engine technologies. These modern dissemination tools offer immersive and interactive experiences that can significantly enhance public engagement with and understanding of architectural heritage (García-León et al., 2018). By leveraging AR and VR, the detailed reconstructions of the Baroque vault can be explored in a contextualized manner, allowing users to virtually navigate through historical spaces and appreciate the architectural nuances and transformations that have occurred over centuries.

Moreover, the utilization of video game engines for presenting these models can introduce a broader audience to the architectural wonders of Valencia Cathedral, transcending traditional boundaries of academic and professional fields (A. Merlo et al., 2013) (Martín-Fuentes & Cabezos-Bernal, 2023). This approach not only democratizes access to cultural heritage but also opens up educational opportunities, enabling a deeper appreciation of historical architecture's complexity and beauty among the general public. Through these technologies, the project transcends conventional documentation and preservation, offering a dynamic platform for experiencing and learning about architectural heritage in an engaging and accessible way.

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