Advanced digital modelling of the Torre del Mar (Borriana, Castellón): from digital fabrication to immersive experience through eXtended Reality (XR)

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Michele RUSSO, Marta ACIERNO (Eds.)

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Advanced digital modelling of the Torre del Mar (Borriana, Castellón): from digital fabrication to immersive experience through eXtended Reality (XR)

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Abstract

The sixteenth-century Mediterranean was neither a secure environment nor its coastlines, necessitating substantial defensive measures. To this end, fortifications were erected around urban centres and many towers were constructed to punctuate the coastal perimeter. The littoral of the Kingdom of Valencia was no exception; indeed, it was particularly affected by the presence of the Morisco population. Within this context emerges our case study: the Torre del Mar (Borriana, Castellón), an optimal site for the experimental methodology proposed in this investigation. Constructed between 1553 and 1558 by viceregal mandate, and subsequently documented by the engineer Giovanni Battista Antonelli in 1563, it constitutes a paradigmatic element of the coastal defensive system, whose comprehension may now be mediated through innovative communication forms. The principal objective of this research is the creation of a comprehensive and detailed digital model, which integrates data obtained through unmanned aerial vehicle (UAV) photogrammetry (specifically processed to maximise the level of detail of the external envelope) with a point cloud acquired through high-resolution terrestrial laser scanning (TLS), for the geometric and material characterisation of internal spaces. The resulting digital model fulfils multiple interpretative and communicative functions. Firstly, it constitutes the foundation for realizing a physical scaled replica, produced through digital fabrication techniques. The physical model decomposes the structure into twelve components, assemblable via magnetic connections. This solution enables dynamic exploration of the tower's constructive elements. Secondly, the digital model is propaedeutic to the development of immersive eXtended Reality (XR) experiences: Virtual Reality (VR), accessible remotely; Augmented Reality (AR), for interaction with the physical model; and Mixed Reality (MR), aimed at creating collaborative environments. This research demonstrates how contemporary digital modelling methodologies offer innovative approaches for analyzing, interpreting, and disseminating fortified heritage.

Keywords: digital survey, digital modelling, digital fabrication, extended reality (XR).

1. Introduction

The sixteenth-century Mediterranean was a landscape of constant tension, necessitating a defensive effort along the Kingdom of Valencia's coasts to counter the Barbary corsairs' incursions (Rodríguez-Navarro et al., 2015). Under the impetus of Viceroy Bernardino de Cárdenas, an extensive system of watchtowers was erected, the design of which was partially documented by the engineer Giovanni Battista Antonelli (Melchor Monserrat, 2015). A paradigmatic case study within this system is the Torre del Mar of Borriana (Castellón), constructed between 1553 and 1558 in a strategic location, proximate to a landing place and a source of fresh water (Melchor Monserrat, 2015). The tower has been the subject of several studies that have outlined its historical and architectural profile. Research conducted by the Municipal Archaeological Museum of Borriana has compiled and systematized the known documentary data and sources (Melchor Monserrat, 2013; Melchor Monserrat, 2015). These are complemented by academic analyses (Celda Cerdán, 2012), which have provided a formal and constructive description of the tower within the framework of a comprehensive catalog of coastal fortifications between Borriana and Puig. Concurrently, comprehensive methodologies for the digital documentation of this heritage have been defined (Rodríguez-Navarro et al., 2015), and the Borriana Museum itself has already undertaken virtualization initiatives for educational purposes (Melchor Monserrat et al., 2016).

The present research investigates the application of an additional digital workflow capable of translating survey data into tangible and immersive engagement tools. The primary objective is creating a high-fidelity, multi-source digital model, obtained by fusing aerial photogrammetry data for the exterior shell with a terrestrial laser scanner (TLS) point cloud for the interior spaces. The novelty of this research resides in the twofold purpose of this model. Firstly, it constitutes the matrix for the digital fabrication of a scaled physical replica, which is disassemblable into twelve magnetic parts, enabling a constructive exploration of the tower. Secondly, the model serves as a prerequisite for the development of a comprehensive ecosystem of eXtended Reality (XR) experiences: from Virtual Reality (VR) for remote immersive engagement, to Augmented Reality (AR) for interaction with the physical model, through to Mixed Reality (MR) for the creation of collaborative environments.

2. Integrated approach combining aerial photogrammetry and terrestrial laser scanning (TLS)

The data acquisition phase was conducted utilizing a methodological approach aimed at maximizing the level of detail for both the external envelope and the interior spaces.

For the exterior survey, a DJI Mavic 3E drone, equipped with a 20-megapixel 4/3-inch CMOS sensor, was employed to acquire 148 high-resolution aerial photographs (5280x3956 pixels). Utilizing a remotely piloted system proved particularly effective for comprehensively documenting the uppermost sections of the structure, which were otherwise inaccessible. The capture parameters were optimized to ensure maximum sharpness, utilizing a 24 mm focal length and a fast shutter speed (1/2000 sec.). This configuration was also designed to produce high-quality textures for the subsequent restitution phase. A significant aspect of this survey was the geolocation of each frame via the drone's integrated GPS; during the photogrammetric restitution, this information enabled the automatic orientation and positioning of the digital model, thereby simplifying and enhancing the accuracy of the overall process.

Concurrently, a high-resolution survey was performed using a Time-of-Flight (ToF) Leica RTC360 TLS for the geometric and material characterization of the interior spaces. The acquisition, executed through 26 scans employing a variable resolution strategy (12 mm and 6 mm at 10 m for the interior; 6 mm and 3 mm at 10 m for the exterior) to cover every environment without occlusion zones, yielded a high-density point cloud comprising approximately 156 million points. With a total file size of 2.8 GB, this dataset served to document the surface's geometry and state of conservation. The acquisition of the external masonry, overlapping with the photogrammetry survey, proved essential for the alignment phase, providing a robust foundation of common homologous points for the accurate and coherent fusion of the point cloud with the model generated from photogrammetry (Grussenmeyer et al., 2012).

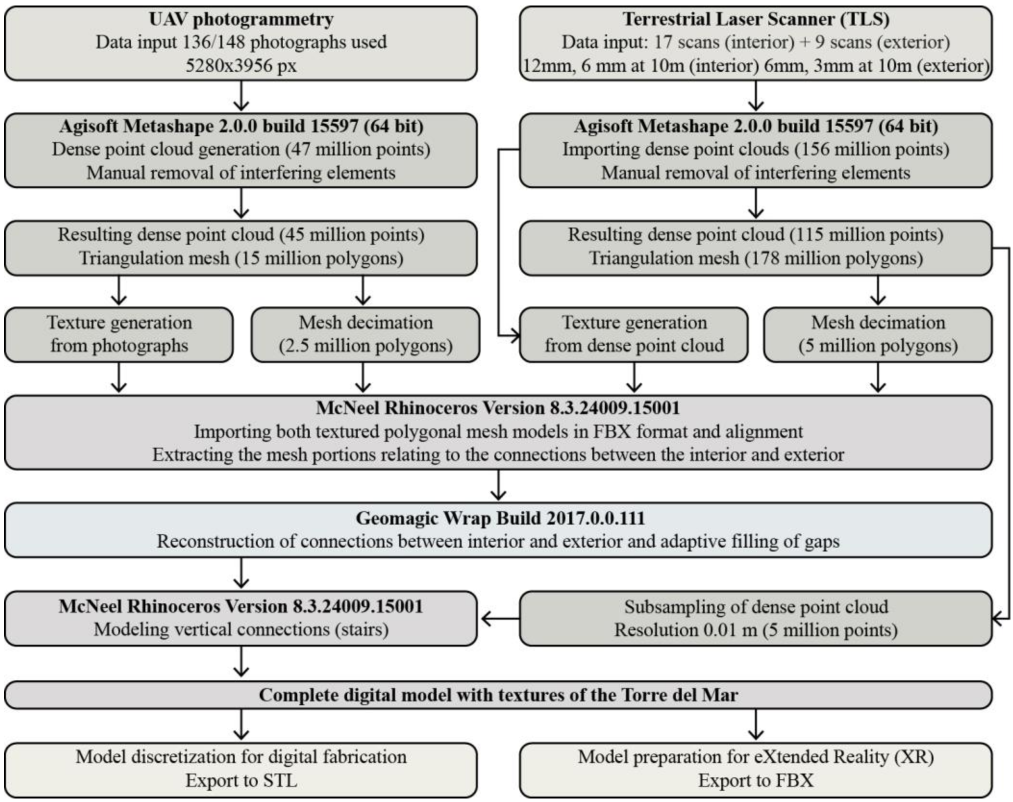

Fig. 1- Workflow diagram for generating the complete, textured digital model, preliminary to the subsequent phases (elaboration by E. Pupi, 2025)

3. From raw data to digital model: processing, optimization, and integration

The transition from the in situ acquired data to a complete digital model followed a structured workflow to coherently manage and integrate the two heterogeneous source datasets. The methodological diagram illustrates the operational process adopted, highlighting the sequential phases and the software ecosystem employed (Fig. 1).

The data processing was initially articulated along two parallel paths, specific to each survey technology. Regarding the photogrammetric restitution, 136 of the 148 photographs were processed. For this purpose, Agisoft Metashape software was selected based on its excellent ratio between processing time and the quality of results (Gil-Piqueras et al., 2019). By leveraging Structure from Motion (SfM) algorithms for image alignment and homologous point reconstruction, and subsequently for densification, a dense point cloud of approximately 47 million points was generated.

This was subjected to a meticulous cleaning phase to eliminate anthropogenic noise extraneous to the artifact’s morphology, which would have compromised the topology of the subsequent mesh triangulation. The resulting dense point cloud, comprising approximately 45 million points, was then utilized to generate a polygonal mesh of 15 million polygons.

To ensure computationally sustainable management, the model underwent a decimation process that reduced its complexity to 2.5 million polygons, while preserving geometric detail in the more complex areas. The final phase consisted of generating the photorealistic texture, achieved by projecting the original images onto the mesh surface through a UV mapping process (Fig. 2).

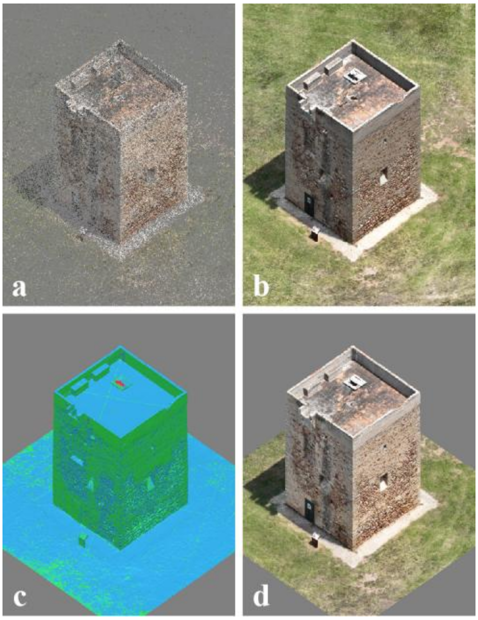

Fig. 2- Stages of the photogrammetric reconstruction process: frames alignment (a); creation of the dense point cloud and elimination of interfering elements (b); triangulation mesh of the point cloud and polygon decimation (c); texture mapping on the digital model (d) (elaboration by E. Pupi, 2025)

Regarding the interior, the dense point cloud of 156 million points, acquired at a resolution of 0.001 m, was imported into Agisoft Metashape. In this case, a phase of filtering and manual removal of extraneous elements was also necessary to isolate the pertinent geometry of the tower.

The resulting dense point cloud, comprising approximately 115 million points, was triangulated to produce an ultra-high-resolution polygonal mesh of 178 million polygons.

The texture mapping was derived directly from the RGB values for each point of the cloud (vertex color). The excessive polygonal density, although accurate, rendered the model difficult to manage; therefore, a decimation was performed, reducing the mesh to 5 million polygons (Fig. 3).

The subsequent phase of the process involved the coherent alignment of the two models. Both meshes were exported in FBX format and imported into the McNeel Rhinoceros modeling environment.

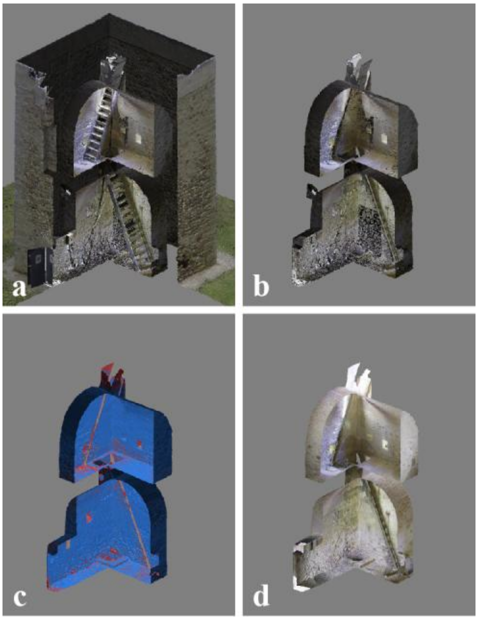

Fig. 3- Stages of the modeling process from the point cloud acquired using TLS: importing the cloud (a); filtering and removing interfering elements (b); point cloud mesh triangulation and polygon decimation (c); texture mapping on the digital model (d) (elaboration by E. Pupi, 2025)

The precise alignment of the two models was facilitated by the overlapping geometric domain constituted by the external masonry surface, present in both surveys, which provided a robust reference.

For the topological stitching of the open edges (at the entrance door, the rooftop hatch, and the arrowslits) and for the adaptive filling of the residual gaps, Geomagic Wrap software was employed, which enabled the generation of a unified mesh.

A final modeling phase was necessary to reconstruct the internal vertical connections, the geometry of which had been removed during the dense point cloud filtering stage. The TLS point cloud was resampled to a resolution of 0.01 m, resulting in an optimized cloud of 5 million points. This was utilized as a metrically accurate reference in Rhinoceros for modeling these elements.

The final result of this process is the complete and textured digital model of the Torre del Mar: a multipurpose digital asset that combines the photogrammetry of the external envelope with the TLS survey of the interior spaces (Fig. 4).

This model represents the starting point for two distinct applications: the digital fabrication of the physical model and the development of Extended Reality (XR) experiences.

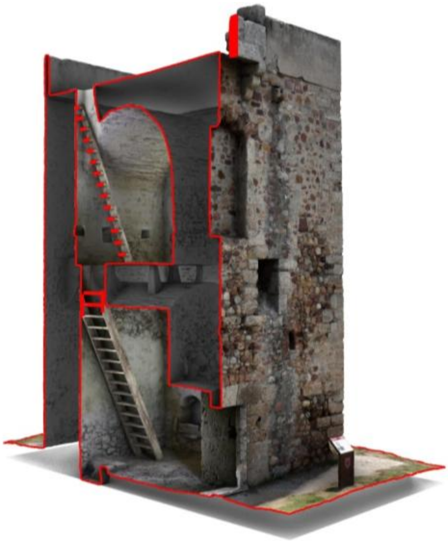

Fig. 4- Result of the digital modeling process, where external photogrammetry and internal laser scanner survey data were integrated (elaboration by E. Pupi, 2025)

4. Translation of the virtual model into a physical model through digital fabrication

One of the objectives of the digital model involves its translation into a physical model, achieved through an additive manufacturing process. This phase required a meticulous reprocessing of the digital asset, no longer oriented toward visual rendering (the textures were removed as they are not pertinent to Fused Deposition Modeling - FDM - 3D printing), but rather toward its engineering for production (Scopigno et al., 2017).

The initial significant decision concerned the selection of the representation scale. A 1:50 scale was considered but given the tower's actual height of approximately 10 meters, the resulting model would have been about 20 cm, a dimension that would have inevitably compromised the high level of morphological detail captured during the data acquisition phase. Consequently, a 1:20 scale was selected, which enabled the creation of a physical model of significant size (approximately 50 cm in height), capable of rendering the masonry texture and constructive details with high fidelity.

Once the model was scaled, it was segmented using sectioning planes. Using two centroidal orthogonal planes was discarded for the vertical subdivision.

This approach, although geometrically simpler, would not have effectively illustrated the complex internal morphology of the arrowslits and openings, which are not aligned with the central axis of the structure.

Therefore, a more sophisticated solution was adopted: the two vertical section planes were positioned asymmetrically, with an offset from the centroid. This choice allowed for the most precise possible exposition of the cross-section of the connections between the interior and exterior of the openings on all four sides of the tower (Fig. 5).

The horizontal subdivision was less complex. Two planes were employed, positioned approximately one meter above the floor level of the ground and first floors, thereby explicating the plans' layout on the tower's different levels. This discretization process yielded twelve distinct parts, designed to be assembled in various configurations, thus permitting a dynamic and customized exploration of the scaled reproduction of the artifact.

Interlocking joints were avoided to make the connections practical and straightforward, as they could have been fragile and complex. Instead, cylindrical housings were modeled within the digital model to accommodate magnetic connectors. This solution ensures easy, intuitive, and robust assembly and disassembly, enhancing the model's interactivity (Fig. 6).

Each component underwent topological validation before the digital fabrication using Autodesk Netfabb software. This step proved essential for identifying and correcting minor mesh imperfections (such as non-manifold edges, tiny holes, stitching issues, and interference shells), thereby ensuring the successful outcome of the digital fabrication process.

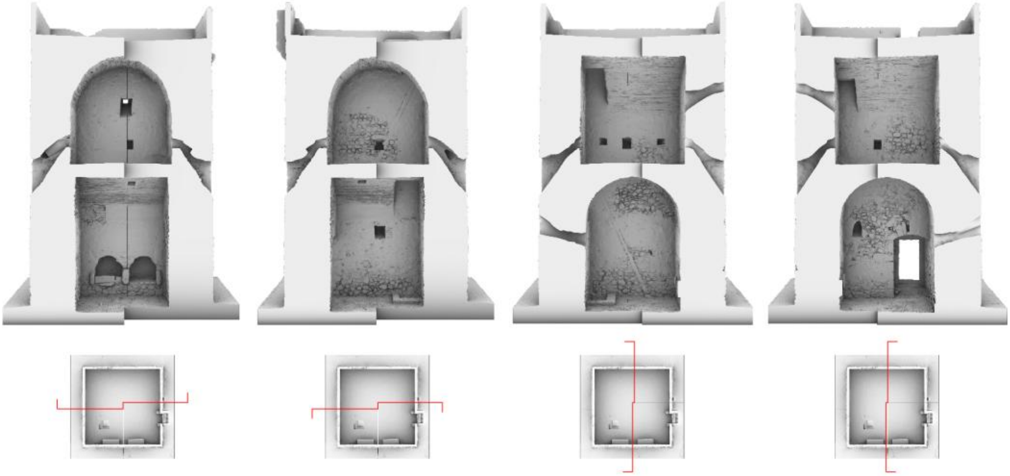

Fig. 5- Perspective views of the vertical sectioning of the physical model. The planes used have been shifted at the center, highlighting the connections between the interior and exterior (elaboration by E. Pupi, 2025)

The possibility of subjecting the model to corrections via digital sculpting with dedicated software (e.g., ZBrush) to further emphasize the materiality of the surfaces was also considered. However, this operation was deemed unnecessary, as the initial digital model already preserved a morphological texture that was extremely faithful to the original and sufficient to guarantee a high-quality result.

Fig. 6- Perspective view of one of the possible breakdowns of the physical model (elaboration by E. Pupi, 2025)

5. Immersive fruition through the development of eXtended Reality (XR) experiences

The research project's second objective focused on transposing the digital model into an asset intended for immersive engagement experiences through Extended Reality (XR).

This approach entails distinct development trajectories: the implementation of an Augmented Reality (AR) application for the informational enrichment of the physical artifact, and the potential creation of collaborative analysis environments in Mixed Reality (MR).

However, the operational focus of the present contribution is dedicated to the rapid prototyping and qualitative validation of a Virtual Reality (VR) experience, considered the most effective modality for a fully immersive simulation.

The process required a specific preparation of the digital asset. The complete model, including the texture mapping and at a 1:1 real-world scale, was exported from Rhinoceros in the FBX format.

This format was selected to preserve the polygonal geometry and the UV mapping coordinates, materials, and object hierarchy.

The preceding optimizations of the mesh density proved to be of fundamental importance at this stage, ensuring the fluid handling of the asset, which is necessary to maintain a stable frame rate during the user experience.

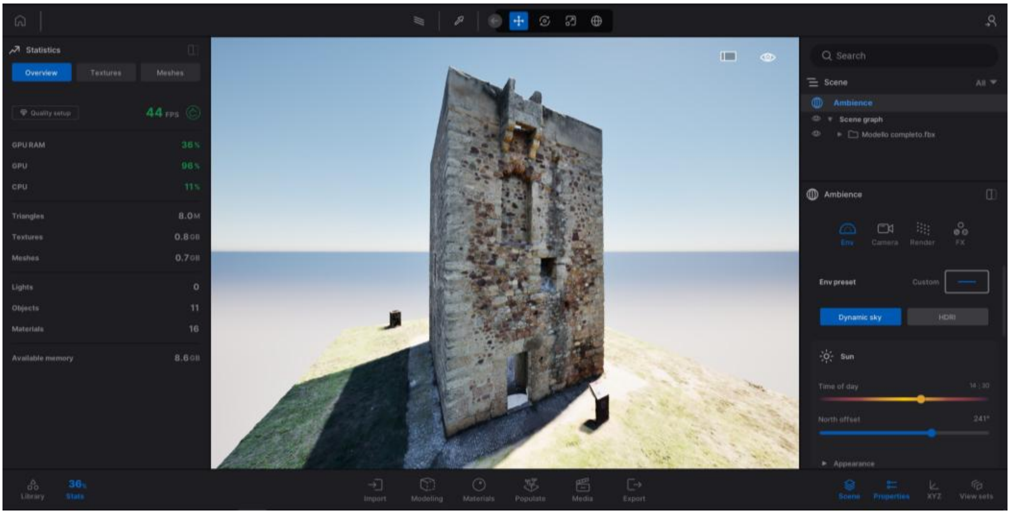

Fig. 7- Importing the model into the Twinmotion workspace and setting the relevant parameters (elaboration by E. Pupi, 2025)

The Twinmotion (version 2025.1.1) work environment was employed for rapid prototyping, testing the application in PCVR (PC-powered Virtual Reality) mode. This choice enabled the host computer to leverage its superior computational capacity and GPU power, thereby overcoming the hardware limitations of a standalone headset and permitting higher-quality rendering without further model optimization.

Once the asset was imported, the global illumination conditions were calibrated to faithfully replicate the ambient light captured during the photogrammetric survey session. This pursuit of photometric coherence between the shadows impressed upon the external texture and the dynamic ones calculated by the rendering engine contributed significantly to increasing perceptual verisimilitude and reinforcing the user's sense of presence within the virtual space (Fig. 7). The experience was validated using a Meta Quest 3 headset, for which a teleportation-based locomotion system was implemented in addition to the 6 DoF navigation. This type of interaction was preferred over continuous movement to mitigate the risk of VIMS (Visually Induced Motion Sickness), a determining factor in designing compelling VR experiences. Maintaining the 1:1 scale of the model is fundamental, particularly in cultural heritage contexts, as it guarantees the user an accurate dimensional perception of the architecture.

User engagement tests yielded positive qualitative feedback. The high resolution of the textures permitted excellent engagement with the digital model, highlighting the state of conservation of the real artifact. Particularly effective was the photorealistic rendering of the interior environments, the texture of which, derived directly from the vertex colors of the point cloud, demonstrated high-quality chromatic and material fidelity (Fig. 8). This result, difficult to obtain with photography alone in confined and poorly illuminated environments, is a direct consequence of the ultra-high density (0.001 m) of the TLS acquisition.

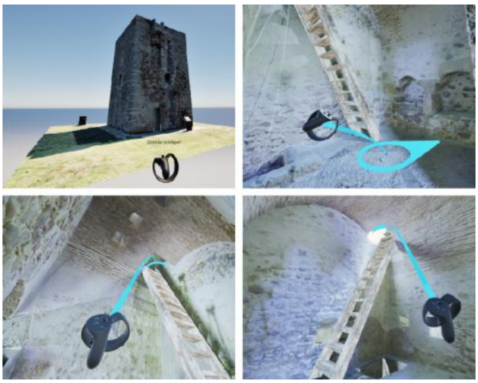

Fig. 8- VR experience test, accessible with 6 DoF navigation or a teleportation system (elaboration by E. Pupi, 2025)

6. Conclusions

The proposed digital workflow can extend beyond the documentation of fortified heritage, transforming metric data into an active instrument for analysis and communication. The principal contribution of this work lies not merely in creating a 3D model, but rather in its conception as a generative matrix model. This paradigm shifts the value of the survey from its archival function to its capacity to generate heterogeneous and functionally distinct outputs: the physical model and an experiential space for immersive engagement.

The project creates a hybrid perception ecosystem. In this system, the understanding afforded by the disassemblable physical model is integrated with immersive experience in VR. This duality offers a more profound and multi-sensory engagement with the cultural asset than a single medium could permit, creating a bridge between digital representation and lived experience. The described workflow qualifies as a replicable and scalable methodological model. Its structure and technologies can be adapted to study other cultural heritage elements, particularly those exhibiting similar geometric complexity characteristics.

This approach also opens further prospects for the comparative analysis of construction techniques and architectural typologies by applying the same methodology to other towers within the Valencian defensive system.

The project contributes to the democratization of access to cultural heritage. The physical and geographical barriers that limit in situ visits are overcome by the virtual experience, making the Torre del Mar accessible even to users with reduced mobility. The physical model constitutes a powerful didactic tool, capable of rendering the tower's architecture comprehensible intuitively.

The research demonstrates how current digital modeling and engagement methodologies offer innovative approaches for analysis and fortified heritage's interactive, inclusive, and multi-sensory dissemination.

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