Interoperability and optimization issues in mixed reality setup for complex built heritage

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Abstract

The research aims to investigate an appropriate mixed reality setup for complex built heritage assets. The process looks into a number of phases, starting from recording, visualization, and interaction, hence from the data processing phase to mixed reality environment management. By comparing the interoperability of 3D file formats, the workflow is optimized to transmit designated data efficiently and seamlessly. The virtual environment setting for built heritage with high-variance mesh is discussed in detail. Interoperability is also highlighted by using multi-level model proxies and resolution variables to decrease the dependence of computation, reducing latency in runtime, and enhancing the interaction input and response agility. Based on the realistic rendering setup for a better sense of presence, the research proposes three sets for level of detail (LOD) to optimize the visualization and performance on MR devices. Limitations and challenges were identified in the workflow with manual reconstruction steps.

1. Introduction

Virtual and mixed reality (VR/MR) are considered to be efficient and inclusive tools for visualization and improved communication of built cultural heritage. Several recent papers focus on optimization techniques for immersive VR experience of cultural heritage and the use of different geomatics technologies for digital reconstruction (Fernández-Palacios et al., 2017; Turchetti et al., 2025), while testing different texture mapping algorithms to simplify the mesh geometry of models constructed from multi-source datasets. Still, there are no steady pipelines that can be used as guidelines during MR environment preparation for assets with complex geometries. From a comprehensive review on visualization in virtual realities (Korkut & Surer, 2023), it can be deduced that, for scientific visualization generally, only a few studies focus on creating standard guidelines for virtual reality, while each study provides an individual framework or it relies on previous traditional 2D visualization studies; more specifically, the most mature research areas on visualization come from training, architecture, and game technologies. One reason for this can be found in the fact that the architecture domain, including historic buildings and archaeological built heritage, already intrinsically relies on 3D representation, and has accomplished the transition to digitalized and virtual environments more smoothly.

Scientific visualization represents the numerical data graphically for qualitative and quantitative analysis and concentrates on 3D volumetric data combined with abstract informative elements (Korkut & Surer, 2023). The data in scientific visualization focuses on continuity in space and time (Peikert, 2009). For example, the digital recording of built heritage documents the spatial characteristics and historical contributions that create the existing condition. Reality-based 3D digitization is conducted for an accurate and photo-realistic digital replica from reality survey and documentation. Successively, massive and complex data requires a holistic method to organize and produce high-fidelity visualization that supports comprehensive research based on graphic information.

The immersive technologies are seen as appropriate tools because they promote the intuitive and often inclusive consultation of recording datasets and their metadata (text, images, models, sounds, animations, etc.), enabling repeatable and non-destructive skill development with trustful digital replicas. To this aim, the iteration in graphic and immersive technologies increases the acceptance of graphics in scientific research (Korkut & Surer, 2023). The processed data requires an effective representation and controlled loading strategies to maintain efficiency while querying the data. Multi-disciplinary approaches involve not only the specialized knowledge of the scientific domains but also that of the MR virtual environment and related application scenarios. The balance between high-resolution modelling and MR photorealistic environment demands optimization of the digitization results for the hardware instrumentation to provide a real-time visualization without introducing noticeable latency.

The research aims to investigate an appropriate mixed reality setup for complex built heritage. The process looks into a number of phases, starting from recording, visualization and interaction, hence from the data processing phase to mixed reality environment management, proposes a method referring to the domain of interactive design. Based on the realistic rendering setup for a better sense of presence, the research proposes three sets for mixed reality level of detail (MR LOD) to optimize the visualization and performance on immersive devices. By comparing the interoperability of 3D file formats, the workflow is optimized to transmit designated data efficiently and seamlessly. The virtual environment setting for built heritage with high-variance mesh is discussed, while interoperability is highlighted using multi-level model proxies and resolution variables. Testing results are illustrated while challenges and best practices have been identified and discussed, to provide some final remarks on the subject.

2. Method applied and interoperability

The first phase is asset preparation: survey data preprocessing, 3D modelling, texture post-production, interoperable format selection according to modelling results, and file export optimization. The recording phase relied on different technologies, obtaining multi-sensor datasets ranging from geodetic network, UAV, terrestrial laser scanning to close-range photogrammetry. The raw data acquired from the survey were recorded in various formats generated by different sensors. Table 1. summarises the survey techniques and datasets used for further processing. The datasets were carefully chosen to encounter the geometric complexities of the single areas considered.

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Technique	**TLS**	**Photogrammetry**	**UAV**	**Geodetic network**
Area considered	Main chambers and single loculus	Atrium	Atrium and dromos ground, contextual landscape	Surroundings of Tomb 7
Instrument	Faro Focus S70	Camera Canon 550D, objective at 10mm	Mavic 3 Enterprise with RTK/PPK module	GNSS, total station
Data used	Approx. 406 million points	136 images	Total 755 images (entire Tombs of the Kings area)	14 points
Resolution	Medium precision 3.0 mm	1.2 mm	10.0 mm	-
Product	Mesh model from point cloud	Mesh model	Digital elevation model	Adjusted control points measurement

Table 1. Data integration for virtual environment import

Model segmentation was performed according to the spatial feature and construction element, providing isolated views of individual spaces and elements. All the mesh models were geo-referenced before export as MR assets, so each model segment can be correctly placed in the virtual environment. The raw point cloud was excluded from the visualization results because this study concentrated on the complex geometry of mesh surface. Given the designated cognitive task and demanded user interaction, it is not always necessary to use 3D models in the highest resolution. Hence, multi-level proxies of the mesh model were also constructed to facilitate different interactive modalities and visual resolutions. The method proposed three major level of detail (LOD) adapted from Schäffer et al. (Schäffer et al., 2021) and the detailed construction criteria were reported as follows:

LOD 0 proxy (3D shape): The proxy is a synthesized planar and cylindrical model derived from point cloud, representing approximated spatial boundary without texture information. LOD 0 performed as an auxiliary element in MR interaction, providing the basic geometry for navigation between the territory and the site, serving as 3D map, information avatar, and defining interaction boundaries (mesh colliders).

LOD 1 texturized proxy (3D shape with texture): The texturized proxy is a synthesized model differentiated building elements derived from point cloud. Colour information was embedded to enhance the materiality of the site. The model was texturized from orthophotos in lower resolution. The surrounding terrain was also integrated as a flat surface texturized from DEM, connecting the model to the environment. LOD 1 provided contextual and spatial understanding, connecting the underground space to the topographic feature. Basic building elements can be identified from this level to inform the spatial features and construction techniques.

LOD 2 geometric state (3D model): The geometric state includes 3D models with different polygonal complexity and multi-resolution texture constructed from photogrammetry. The decimation process focused on surface simplification, providing low-polygonal proxies. The contextual topography was represented by its depth. LOD 2 visualized the low-polygonal model for quick statistical inquiry and space division, while the high-polygonal model enhanced the sense of presence and provided detailed geometric and colour information.

The second phase is the definition of loading strategies: (i) scene template for common assets and environment settings; (ii) single scene setting based on cognitive contents; (iii) trigger setting for scene switching and activation. 3D assets were imported into Unity due to its well-supported real-time rendering and interaction development. Render pipeline and shaders were selected according to visual realism and runtime speed. Each scene was defined for different study tasks: territorial context, individual monument volume, geometric feature, constructive elements, and superficial engraving. The simplified models were selectively rendered when switching to the corresponding LOD and scale. Simplified LOD0 models were utilized as mesh collider components to avoid manual collider construction in Unity according to the structural boundaries, because assigning mesh colliders directly to the complex surfaces cannot perform correctly. This step decreased the computation demand. On the other hand, the carved underground surfaces lack explicit structural thickness, which demanded the synthesized collision to maintain the continuity of the inner space.

Texture and material properties were integrated into the asset packages for rasterization rendering. The global render setting was improved by selecting suitable render pipeline and shader. The proposed users were learners in the geomatics-related fields. The interactive modalities concentrated on the natural spatial navigation and observation, with single isolated views for close observation of individual elements. A single-user perception was defined by the collision detection, player-following camera and interactive input and response, and the full Unity project was finally compiled into MR application for android mobile devices. The testing hardware is a head-mounted device (HMD) Meta Quest3 (Qualcomm Snapdragon XR2 Gen 2, 8GB memory).

The MR setup criteria for complex built heritage recording consider geometric fidelity, realistic rendering and real-time interaction (Bolognesi & Manfredi, 2024). Before MR development, it's crucial to consider the interoperable formats to help avoid conversion, reduce processing time and prevent potential data loss. The format selection refers to the following aspects: (i) compact file size; (ii) appropriate recorded information (geometry, texture, coordinate system); (iii) readable and editable in the used software. This step will be important to decrease latency in the MR development. Table 2 reports the major criteria related to 3D file format interoperability.

Criteria	Properties
Data category	Point cloud; Image; Model
Contents	Mesh; Texture; Material; Lighting; Camera; Animation; Scene
Transmission possibility	Data processing software; Virtual experience development platform
Proprietary status	Open standard; Proprietary

Table 2. Interoperable factors: 3D file format selection criteria

3. Method testing and main results

The proposed approach was tested on the MR preparation of Tomb 7, Tombs of the Kings, a UNESCO World Heritage Site in Paphos, Cyprus. Used as cemeteries from the early Hellenistic period and the Roman period, Tombs of the Kings underwent adaptations in functions. The complex includes various types of rock-carving tombs as unique cases in the extended area. Tomb 7 is partially underground and is accessible through the dugout dromos, leading to the atrium which is surrounded by a colonnade with three remaining columns. Two burial chambers with loculi are connected by openings on the lateral walls. The whole construction is risked by structural deterioration and crack. Tomb 7 exhibits irregular protuberances contributed from manual treatment and coastal erosion, which risk oversimplification and characteristic loss in the digitization process. A brief workflow of the proposed solution is reported in Figure 1.

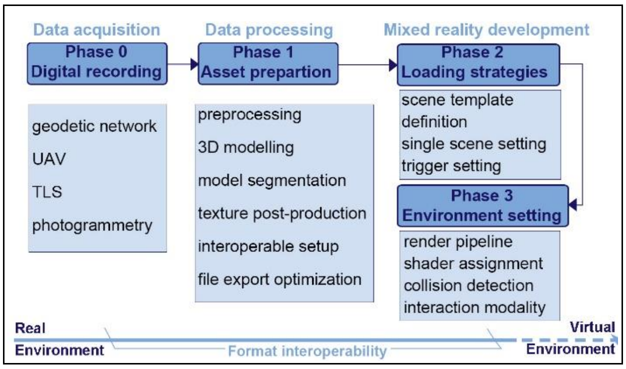

Figure 1. Workflow of modelling and mixed reality setup

Tomb 7 is characterized by complex convex surface of eroded rock with a similar beige color. The limited illumination inside the underground chambers and confined space for operation were challenging for digital recording. The integrated data from various sensors were employed in MR creation and represented as Figure 2. The complexity of the raw data demanded an optimized workflow in data processing, as the raw data were derived from multiple sources. Its visualization required unnoticeable latency to ensure a real-time immersive experience.

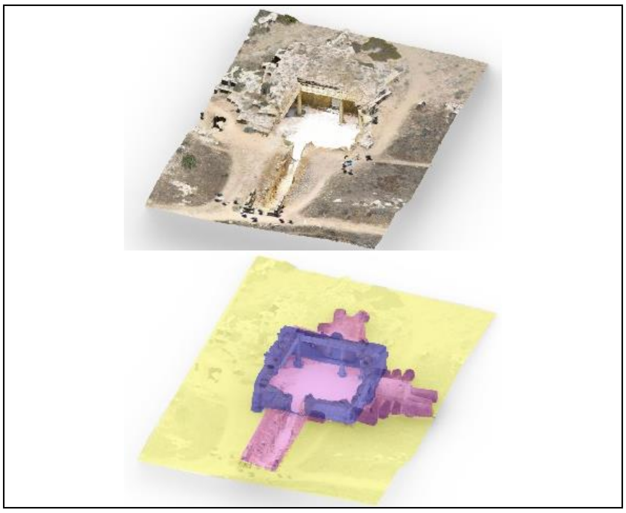

Figure 2. LOD 2 mesh model: data sources (yellow: UAV photogrammetry, blue: TLS, pink: photogrammetry)

3.1 Interoperability issues

The proposed format selection promotes overall workflow efficiency, reduces manual conversion efforts, and saves time and storage requirements of transitional files. However, rapid technological iteration implies the potential obsolescence of formats and related software and hardware (Koehl et al., 2024), which requires the scalability to be converted when reaching end-of-life. It is worth noting that open standard formats break through certain proprietary limitations in heterogeneous platform exchange. This allows collaboration in teamwork to share assets across different specialized software without data loss (Cyprus University of Technology, 2022). In this term, file format

category	format	Recap		Metashape		Rhino		Blender		Unity	Unreal
		I	E	I	E	I	E	I	E	I	I
point cloud	▨ ASCII PTS (*.pts)	🟩	🟩	🟩	🟩	🟩		🟧	🟧	🟧	🟩
	▨ ASTM E57 (*.e57)	🟩	🟩	🟩	🟩	🟩		🟧	🟧	🟧	🟩
	▨ TXT (*.txt)	🟩			🟩	🟩	🟩				🟩
	▨ ASPRS LAS (*.las)			🟩	🟩			🟧	🟧		🟩
	▨ LAZ (*.laz)			🟩	🟩			🟧	🟧		🟩
	▨ XYZ (*.xyz)	🟩				🟩				🟧	🟩
	🟨 RECAP PROJECT (*.rcp)	🟩	🟩							🟧	
	🟨 RECAP SCAN (*.rcs)	🟩	🟩								
	▨ ASCII PTX (*.ptx)	🟩								🟧	
image	▨ JPEG (*.jpg, *.jpeg)			🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	▨ TIFF (*.tif, *.tiff)			🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	▨ PNG (*.png)			🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	▨ BMP (*.bmp)			🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	🟨 TARGA (*.tga)			🟩	🟩	🟩		🟩	🟩	🟩	🟩
	▨ Scalable Vector Graphics (*.svg)					🟩	🟩	🟩	🟩	🟩	🟩
	▨ OpenEXR (*.exr)			🟩	🟩			🟩	🟩	🟩	🟩
	▨ JPEG 2000 (*.jp2, *.j2k)			🟩	🟩			🟩	🟩	🟩	
	▨ Adobe PDF (*.pdf)				🟩	🟩	🟩				
model	▨ Stanford PLY (*.ply)			🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	▨ OBJ (*.obj)			🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	▨ GL Transmission Format(Binary)GLB (*.glb)			🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	🟨 FBX (*.fbx)			🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	▨ GL Transmission Format GLTF (*.gltf)					🟩	🟩	🟩	🟩	🟩	🟩
	▨ COLLADA (*.dae)				🟩		🟩	🟩	🟩	🟩	
	▨ Alembic(*.abc)				🟩			🟩	🟩	🟩	🟩
	🟨 DXF (*.dxf)				🟩	🟩	🟩	🟩		🟩	
	🟨 3DS (*.3ds)				🟩	🟩	🟩	🟩			🟩
	▨ Universal Scene Description (*.usd)						🟩	🟩	🟩	🟩	🟩
	▨ STL models (*.stl)				🟩	🟩	🟩		🟩		
	▨ X3D models (*.x3d)				🟩		🟩	🟩	🟩		
	▨ VRML models (*.wrl)				🟩	🟩	🟩	🟩			
	▨ Rhino 3D Model (*.3dm)					🟩	🟩				🟩
note:	I: Import, E: Export										
legend:	▨ : open-source, 🟨 : proprietary, 🟩 : native support or native plugin support, 🟧 : only third party plugin support										

Table 3. Analysis of interoperability between raw data, processing software and game engines, elaborated by authors

selection is the fundamental MR optimization in compression rate, operation speed and data storage. In Table 3, the format interoperability between raw data, processing software and game engine was analysed.

From raw data to processed model, open-source formats take a large proportion of the software and game engines throughout the asset preparation and MR development. In addition to the interoperability of the supported formats, the information that each format contains should also raise attention for immersion level enhancement and interactive experience design. The format interoperability not only serves data transmission in the workflow but also defines the richness of the potential interactive elements. Seven information storage categories were identified to ensure the scalability of each format: mesh, texture, material, lighting, camera, animation, and scene. It’s worth noting some extensible data can be embedded in specific formats, for example, COLLADA (*.dae) supports physics simulation. This feature can be explored in further LOD settings. GL Transmission Format Binary (GLB) is an efficient transmission 3D file format containing the aforementioned seven information categories. GLB enables interoperable use of content across the development platforms. The exported 3D assets were compact in terms of file size compared to PLY and OBJ formats. Hence, GLB format was selected in this study to proceed with the later steps.

3.2 First results

High-polygonal model aims to represent the recorded objects at their highest resolution. However, millions of meshes with high variance of the normal will result in a large file size, which consumes computation capacity and hinders the development and testing on mobile and head-mounted devices (HMD) due to the exceeded memory capacity of mobile devices. Therefore, proxy models were applied in both collision detection and geometry visualization in Unity to balance the visual fidelity and performance. Each level was customized according to Tomb 7.

3.2.1 LOD 0 construction

In the data processing phase, LOD 0 was manually modelled from point cloud and reported in Figure 3.

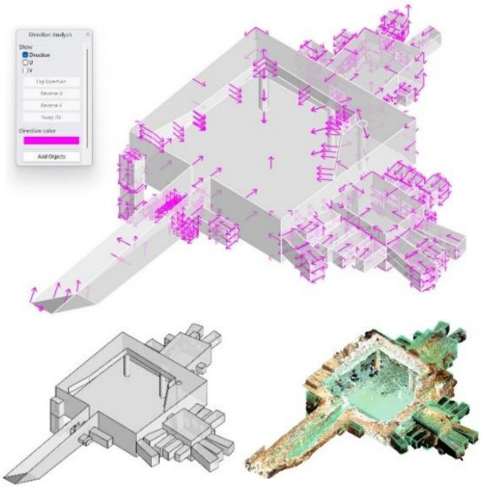

Figure 3. Top: LOD 0 UV direction as front; down: LOD 0 as bounding volume from point cloud

In the modelling process, curvature features such as vaults in the chambers were reconstructed at the highest point as a plane. Columns were unified as cylinders. Some inaccessible spaces (well) were integrated with indirect measurements to complete the geometry and possible site function for documentation reasons. Face directional check was required, because in Unity faces in collision meshes are one-sided. This means 3D assets can pass through from one direction but collide with them from the other. So, the interaction boundary was the front faces towards the users, as indicated in the arrows.

3.2.2 LOD 1 construction

LOD 1 aimed to connect the carved space to the earth's surface with a translucent visualization mode. In LOD 1, the texture was compressed in low resolution when used for territorial understanding. Wall elements were reconstructed in planar mesh with texture derived from orthophotos (Figure 4). Columns reconstructed according to the centres and diameters of the top and base, capitals were reconstructed based on the rectangular edges, and semi vaults were simplified as planar surface extrusion. Geo-referenced orthophotos were inserted in modelling software to keep a coherent scale. Attention should be paid to building element recognition at this level, for example, rectangular capitals should be modelled to inform the construction techniques of the column erection, giving priority to cognitive function rather than being confined to the visibility from the distance. Because in LOD 1, construction knowledge should be introduced, and over-simplification in this level could create confusion before switching to LOD 2 model.

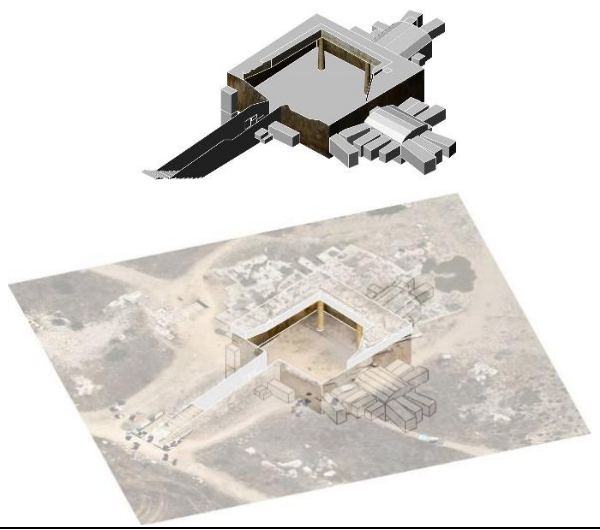

Figure 4. LOD 1 model and context

3.2.3 LOD 2 construction

To create full assets for LOD 2, the mesh models from various sources were integrated and reported in Figure 2. In LOD 2, model segmentation was defined as follows: (i) adjacent terrain, (ii) dromos, (iii) atrium wall and entablature, (iv) column and connected capital, (v) chamber, (vi) loculus, (vii) ground of atrium and chambers. Considering (vii) was not the major survey object, but it provided contextual information, the mesh of (vii) was reconstructed with fewer sampling points in modelling software to simplify the mesh in these areas. Model buffer areas were reserved to maintain enough overlap between the segments, ensuring a continuous surface and sense of reality. The individual trimmed mesh models shared overlapping areas around 10-20 cm. When imported into Unity, chromatic differences could be observed due to various survey techniques. Post-production of the texture was carried out to reduce the light-shadow contrast on the surface. Mesh derived from TLS point cloud provided geometry without colour information. This procedure ensured an accurate model not only for visual appearance but also for further 2D drawing extraction. Noise of the point cloud was manually removed to optimize the mesh generation.

3.3 Assets optimization

Decimation and texture resolution were defined according to spectator distance and demanded detail level. Details decrease when the distance between the viewer and the models increases, but high-resolution assets cannot simply apply the automatic culling of visibility, as the full model will be calculated in the culling.

3.3.1 Method testing on column C4

The testing dataset included column C4 from Tomb 7. Located in the colonnade opposite the dromos, column C4 is to the left when entering the atrium from the dugout passage. This corner column provides structural support for both sides of the colonnade. Results were assessed and reported in Table 4.

Polygonal complexity	High-polygonal	Low-polygonal
Image used	77	
Number of vertices	33,748,710	525,109
Number of faces	6,056,339	114,406
File size	155 MB	13.2 MB
Texture resolution	0.206 mm/pix	0.201 mm/pix
Frame rate	228.2	263.2
Latency	4.4 ms	3.8 ms

Table 4. Column model specification and runtime assessment

3.3.2 Method testing on the whole monument

Following the testing column C4 asset preparation, the decimation was employed on the whole Tomb 7 model. The decimated low-polygonal proxies were generated for all the model segments. From visual realism inspection, the low-polygonal mesh model satisfied brief spatial understanding and quick navigation. For detailed geometric observation, the high-polygonal mesh model provided a sharper texture, which was coherent with the carving traces (see Figure 5. top).

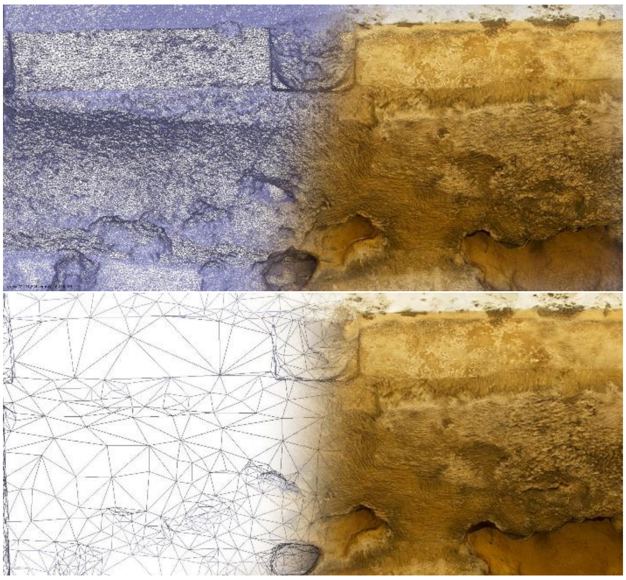

Figure 5. High-polygonal and low-polygonal mesh with texture

To accommodate first-person interaction in MR, mesh colliders were assigned to LOD 0 model, which was manually constructed from the meticulous synthesis of the point cloud, according to the structural boundaries, instead of assigning mesh colliders directly to the complex model mesh. According to bounding volume hierarchies (BVHs), the memory is consumed by the depth of the hierarchy tree (bounding levels) and the type of bounding volume. On every level, the collision test is carried out and ends when no collision is detected on one level. LOD 0 model performed as an artificial bounding volume from the first level of the collision hierarchy and utilized a synthesized mesh to eliminate subdivision of the LOD 2 high-resolution models.

On the other hand, the carved underground surfaces lack explicit structural thickness, which demanded the synthesized collision to maintain the continuity of the inner space. Compared to manual insertion of box and capsule colliders in Unity, the proxies for colliders increased the efficiency of the workflow and enabled the update and transmission throughout the whole process. This collision proxy approach divided the graphical visualization and physical boundary behaviour separately, ensuring a consistent experience between interactive input and response. Challenges were identified from the asymmetry in the graphical and physical behavior of the complex mesh surface, due to the visibility of the given LOD and the memory optimization issues. This step decreased the computation demand. The rendered geometry and collision detection were reported in Figure 6.

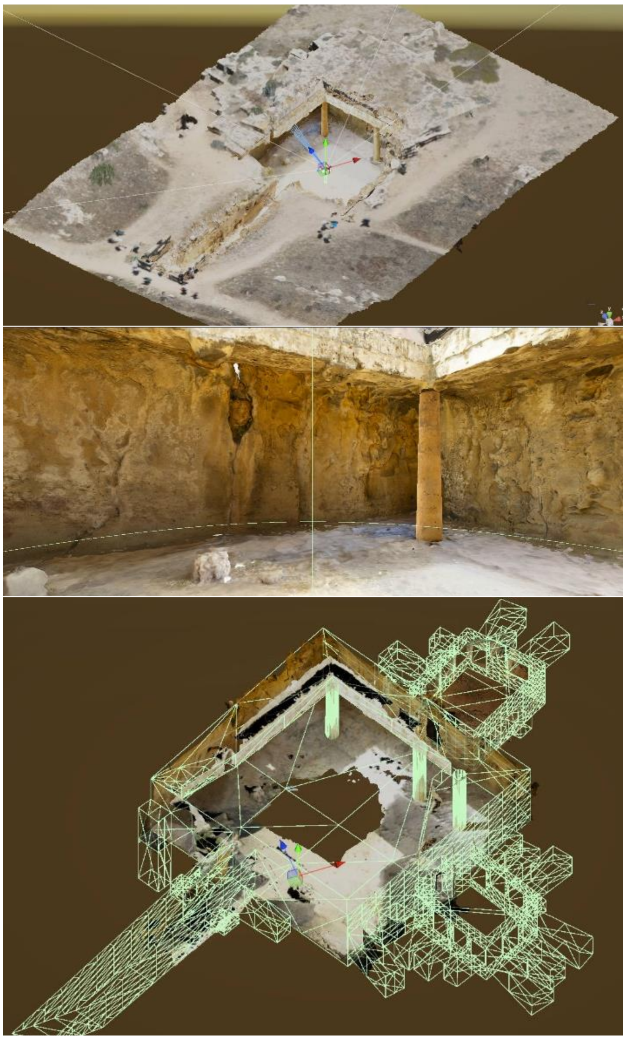

Figure 6. Tomb 7 in virtual environment: top: camera rig; middle: corresponding view; bottom: LOD 0 as mesh collider

Unity applies physically based rendering (PBR) using metalness-roughness material system to increase the sense of presence with realistic rendering compared to the reflection system (ambient, diffuse, specular). The metalness-roughness material system can be assigned before importing into Unity, supporting seamless and efficient transmission, because a single 3D file is more compact than a complete Unity project, which includes all the scenes and assets. In addition to universal render pipeline for 3D projects, Unity supports customized shaders by programming language to improve render representation with environmental illumination and material appearance. Still, the light and shadow effect from the data acquisition phase may contribute to chromatic differences and the loss of detail, which demands an appropriate outdoor environmental condition for the survey. Hence, the generated texture was inspected and post-processed to be correctly visualized before import into Unity. In addition to visual results, optimized shader enhances runtime performance, especially on mobile platforms with limited GPU capacity.

Virtual environments and interface design aim at maximizing user interaction and immersion. A user-centric approach enables a comprehensive understanding of user needs, preferences, and LOD satisfies a designated cognitive task and study target. The testing project is controlled by the benchmark for MR: real-time: Frame rates are expected to be at least 60fps, potentially higher up to 90 fps; latency: less than 20ms (Dörner et al., 2022). The tested latency with the proxies satisfied the real-time interaction of the virtual visit in Tomb 7 without creating cybersickness. The high-resolution spaces include atrium as the exterior centre, which communicates the two burial chambers: chamber W is located in front of dromos, and chamber N is connected by the opening under the destroyed colonnade. LOD visualizations were represented in Figure 7 and Figure 8, and the details were reported in Table 5.

LOD	Location	Faces	Vertices	FPS	Latency
0	Context of Tomb 7	8.3k	11.4k	235.0	4.3ms
1	Tomb 7	900.7k	486.9k	266.8	3.7ms
2	Atrium	9.9M	5.1M	295.9	3.4ms
	Chamber N	61.2M	31.1M	79.7	12.5ms
	Chamber W	6.7M	3.8M	172.1	5.8ms

Table 5. Latency testing of the proposed scenes and LOD

Figure 7. Visualisation of the Tomb 7 in MR environment: left: LOD 0 in the Kings of the Kings territory; right: LOD 1 closeup

Figure 8. LOD 2 visualization in MR environment:
top: atrium, column C4 on the left side; bottom: chamber W, white mesh area: no colour information available

4. Discussion of main findings

During the testing phase, both on a single technological element (column) and on the entire monument (Tomb 7), several aspects have been observed. Considerations here regard (i) the challenges of the dataset type (mesh surface models); (ii) the correct orientation and georeferencing of the environment; (iii) application (gaming) character; (iv) GPU vs. model complexity for proper (sickness-free) experience.

In 3D modelling domain, the conversion from point clouds into mesh models has certain limitations for the visualization and interaction in the MR virtual environment. The main challenge arises from the physical characteristics of the mesh model, which hinder the recognition and effective utilisation of these entities. The discrete nature of polygonal meshes results in a certain level of approximation when representing three-dimensional objects. The accuracy of the non-planar geometry depends on the increase in the mesh, resulting large file size (Banfi et al., 2023). The decimation process can automatically decrease the faces, but the procedure risks over-abstraction, an aspect particularly disadvantageous in built heritage domain.

In the MR asset preparation phase, roto-translation issues should raise awareness in model export and transmission into game engines, because game engine such as Unity uses a different spatial coordinate system from photogrammetric and modelling software: Unity refers to Y axis as third dimension, while in traditional recording practice, this dimension is reserved as Z axis. Therefore, a careful and appropriate conversion of the values in the export step is necessary to avoid rotation of assets in virtual environment setting. Another frequent issue is GNSS coordinate information embedded in the geo-referenced models. The coordinates are too big for modelling software, which could potentially cause original precision loss and deformation of models.

Another critical aspect lies in the domain of application, original MR applications are often associated with gaming (i.e. fully virtual) domain, rather than with scientific applications for heritage recording and digitalisation. Hence, functions are clearly not designed for scientific visualization of complex geometries, which can represent a challenge during environment preparation. In addition to universal render pipeline for 3D projects, game engine like Unity supports customized shader by programming language to improve render representation, using environmental illumination and material appearance. Still, the light and shadow effect from the data acquisition phase may contribute to chromatic differences and the loss of detail, which requires a special lighting set-up during recording.; this issue underlines the importance of special lighting set-up during recording. During testing phase on Tomb 7, the generated texture was inspected and post-processed to be correctly visualized before the import into Unity.

In addition to visualisation aspects, it was noticed that the use of optimized shader enhances runtime performance, especially on mobile platforms with limited GPU capacity. Furthermore, the memory capacity of single device requires for complex geometry mesh model to be simplified in order to provide real-time interaction. This process requires careful planning and skilled operator engagement: HMD sickness may occur when the mesh is oversimplified or the texture resolution is not appropriate (high enough).

5. Conclusion

High-fidelity virtual environment of complex built heritage monuments and sites is necessary to ensure a coherent, realistic experience in MR. When used for education purposes, it enables rigorous analysis of texture, surfaces, potential distinction among technological elements and their respective metadata. The main effort of this paper focused on studying, identifying and testing the following technological aspects during virtual environment development process: (i) the extensive applications of immersive technologies; (ii) the considerations on interoperability between raw data, data processing and virtual experience construction and (iii) open standards that can facilitate regulation and standardization of the MR development.

Several common scientific visualisation elements were identified among the overlapping disciplines, such as: (i) 2D planar and sectional views in various scales; (ii) polygonal wireframe for surface complexity; (iii) texturized surfaces presenting technical elements. Oppositely, the main challenges focus on striking a balance between technology potential and visualization precision, especially in the case of irregular and complex geometries, such as archaeological sites characterized by rock-carving architecture. The proposed method based on MR LOD provided the possibility to choose an appropriate mesh generation and virtual environment settings for each scale, while maintaining a multi-level organization of information. The next step of this research regards the association of cognitive tasks with different data sources and hence different LODs. Virtual environments and Mixed reality provide immersive and inclusive experiences and facilitate access to single monuments or sites even remotely. The intuitive organisation and possibility for repeatable experience make mixed reality an essential tool for future education programmes and knowledge transfer practices in the domain of built cultural heritage.

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