

Integrated System for the Digitization of Cultural Heritage Objects through Photogrammetry and Virtual Reality Visualization

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ABSTRACT

The preservation of cultural heritage has long been recognized as a global priority by major organizations worldwide, as it helps societies understand and protect their historical identity and values. However, cultural heritage objects are often difficult to access, due to their fragile condition, restricted storage environments, or geographical limitations. The solution to all of these issues is the 3D digitization of cultural heritage objects, which can be combined with immersive virtual reality for an enhanced user experience. Despite its potential, 3D digitization can be quite challenging, as it often requires high-end technologies that come at a big cost. This paper proposes an integrated end-to-end system that provides a cost-effective solution, in which users need only a smartphone to digitize an object, and a Meta Quest 2 headset to explore the resulting model in virtual reality. The main contributions of this work are: (1) a fully automated AliceVision-based photogrammetric pipeline integrated into a mobile capture workflow; (2) a native Android application for image acquisition, job monitoring, and 3D model preview; and (3) a Unity-based VR application for the Meta Quest 2 enabling interactive exploration of reconstructed models through the ChemiNova portal. The proposed system requires only a smartphone for digitization and a Meta Quest 2 headset for immersive exploration, without requiring specialized technical knowledge from the user.

Author Keywords

Photogrammetry; AliceVision; Meta Quest 2; Virtual Reality; Cultural Heritage; Object interaction; 3D Digitization; Unity; Android.

ACM Classification Keywords

H.5.1. Multimedia Information Systems; H.5.2. User Interfaces; I.3.7. Three-Dimensional Graphics and Realism; I.4.1. Digitization and Image Capture

General Terms

Human Factors; Design; Measurement.

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INTRODUCTION

Over the past few years, digitization made its way through a wide range of domains. The current tendency is to bring an increasing amount of information and data into the digital realm, with the aim of making it more available to the general public while also ensuring long-term preservation and secure storage. Moving beyond files, documents, and sketches, this evolution has led to a desire to digitize 3D objects, primarily for the purpose of preservation.

Cultural heritage represents one of humanity's most valuable assets, serving as a bridge between the past civilizations and future generations. The digital preservation and documentation of artworks, monuments, and artifacts contribute significantly to their protection while also increasing accessibility for researchers and the general public. These matters are recognized as a priority at an international level, with organizations such as UNESCO and the Council of Europe emphasizing the importance of adopting modern documentation and preservation methods [1, 2]. Digitization also overcomes limitations associated with physical access to heritage objects, mainly caused by the fragility of the objects, geographical distances, or restrictions imposed by the institutions holding them.

In this context, two-dimensional documentation techniques, such as photography and descriptive records, are no longer suitable, as they do not provide enough details for capturing the full spatial and geometric complexity of the three-dimensional objects. As a result, new techniques emerged, being capable of capturing and reconstructing the surface details, texture and geometry of the objects.

One of these techniques is photogrammetry. Recognized as one of the earliest contactless measuring techniques, as it is specified in [3], photogrammetry gained popularity as an accessible and precise method that generates 3D models out of 2D images [4, 5]. While LiDAR provides high geometric accuracy, it requires expensive, specialized equipment. Digital photogrammetry using Structure from Motion (SfM) and Multi-View Stereo (MVS), requires only a set of

overlapping pictures captured from different viewpoints using conventional cameras or smartphones.

While the digitization of cultural heritage has sparked interest, virtual reality (VR) has also evolved to the point of reaching the consumer market and being available to the general public. VR enables users to interact with the digital world through headsets and controllers. Recent studies indicate that immersive VR experiences facilitate easier information retention, showing a 20-35% improvement over traditional presentation methods, and can increase museum visit duration by up to 60% [6].

Despite the existence of isolated solutions for 3D scanning and VR visualization, there is no comprehensive solution that covers the entire workflow and is accessible to the entire public, especially for Android users. The integration of photogrammetry and virtual reality therefore creates new opportunities for cultural heritage preservation and public engagement.

This paper proposes a fully integrated system that allows users to capture images via an Android app, automatically process them into 3D models using an AliceVision-based pipeline, store them in the ChemiNova web portal, and interact with them using a Meta Quest 2 VR application.

RELATED WORK

Digitization of cultural heritage

The digitization of cultural heritage is a rapidly expanding interdisciplinary field that combines advanced 3D capture technologies, digital databases, and immersive visualization methods. Its primary goal is the preservation and documentation of artworks, historical monuments, and archaeological artifacts, while improving their accessibility for researchers and the general public. Major projects such as Google Arts & Culture [7], Smithsonian 3D Digitization [8], and Europeana [9] have demonstrated the significant potential of digital technologies to bring heritage closer to audiences worldwide.

In 2021, the European Commission published a study addressing quality in the 3D digitization of tangible cultural heritage, highlighting the need for clear standards regarding the capture, processing, and storage of digital heritage assets [10]. The study identifies photogrammetry, laser scanning, and structured-light scanning as the primary 3D capture techniques. While laser scanning generally provides superior geometric accuracy, it requires specialized equipment. In contrast, photogrammetry offers an excellent balance between cost and quality. In [11], the authors propose a hybrid approach combining LiDAR with SfM photogrammetry, achieving error rates of less than 5% for small objects and less than 2% for large objects. This observation motivated the choice of pure photogrammetry for the present system, as the heritage objects in scope are small to medium in size and have rich textures, conditions

under which photogrammetry produces results comparable to hybrid solutions at significantly lower cost.

Photogrammetry and 3D reconstruction

According to [12], photogrammetry is the technique for determining the shape, dimensions, and spatial position of objects based on images. This technique relies on Computer Vision algorithms, such as Structure from Motion (SfM) and Multi-View Stereo (MVS). These methods possess the ability to generate an object's or scene's 3D structure from a set of overlapping images captured from different angles, as illustrated in Figure 1 [13]:

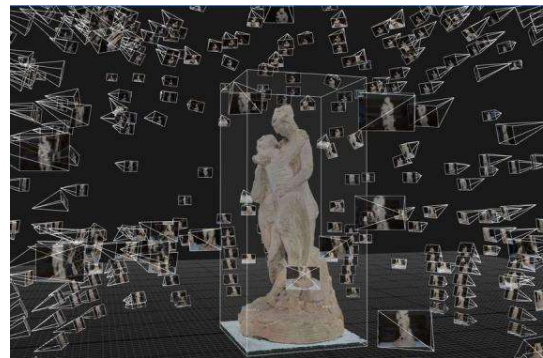


Figure 1. Structure from Motion photogrammetry process [13]

The study in [14] confirms that SfM is suitable for 3D scanning systems that are constrained by the available resources, demonstrating that historical documents and heritage objects can be digitized using only a smartphone and a laptop, without specialized acquisition equipment.

Among available software solutions, Meshroom, built on the AliceVision framework [15], represents one of the most comprehensive open-source pipelines. It consists of 11 main steps: CameraInit, FeatureExtraction, ImageMatching, FeatureMatching, IncrementalSfM, PrepareDenseScene, DepthMap, DepthMapFilter, Meshing, MeshFiltering, and Texturing.

Virtual reality in cultural heritage

In parallel with advances in digitization technologies, virtual reality evolved in many areas, becoming a powerful tool for preserving and promoting cultural heritage. Through VR headsets, users can be transported into digitally reconstructed environments, allowing them to explore archeological sites, museums, or historical monuments as if they were physically present.

An analysis of 142 studies published between 2015 and 2025 [6] identified five major research directions in VR/AR applications for digital museums: immersive storytelling, visitor engagement, hybrid physical-digital exhibitions, heritage reconstruction and technological ecosystems. The study reported that VR experiences increase information retention rates by approximately 20-35% compared to traditional presentation and learning methods, while also extending visit duration by up to 60%.

Notable VR applications for cultural heritage include British Museum VR [16], which enables users to examine artifacts in detail, and Versailles VR [17], which offers an immersive experience of the Palace of Versailles. However, both rely on pre-authored 3D assets requiring substantial manual production effort. Similarly, commercial photogrammetry applications such as Polycam and RealityCapture perform 3D reconstruction but do not integrate directly with institutional content management systems or provide immersive VR visualization.

Table 1 compares the proposed system with representative existing solutions, highlighting the gaps that the present work addresses across the complete digitization workflow.

Feature	Polycam	Reality Capture	Proposed System
Mobile capture	iOS only	No	Yes
Automated 3D reconstruction	Yes	Yes	Yes
Multiple output resolutions	No	Yes	Yes
Management System integration	No	No	Yes
VR visualization	No	No	Yes
Open-source	No	No	Yes
Cost	License fee	License fee	Free

Table 1. Comparison with existing solutions

As shown in Table 1, no existing solution covers the complete workflow from Android-based mobile capture through automated reconstruction to institutional storage and immersive VR visualization within a single open-source platform. The system proposed in this paper is the only solution in this comparison that addresses all of these requirements simultaneously.

THEORETICAL FOUNDATION

The main objective of this paper is the integration of 3D digitization and immersive VR visualization into a single end-to-end system. To achieve this, several functional requirements were identified: the user must be able to capture and upload photos from the phone through a Flask server; the processing status of each step must be displayed in real time; the user can cancel processing at any time; the user can select the desired level of detail; before uploading to the portal, the user can preview the model in an integrated 3D viewer; and the system must be accessible regardless of the local network.

Photogrammetry reconstruction

Photogrammetry represents the technique that reconstructs object geometry by identifying corresponding points across multiple overlapping photos and determining their spatial relationships. The process begins with camera calibration: intrinsic parameters are estimated from EXIF metadata and refined during reconstruction. The most important stage is represented by Structure from Motion, implemented incrementally in AliceVision: starting from an initial image pair, additional images are progressively registered using SIFT-based feature localization. To efficiently identify suitable image pairs, AliceVision uses a vocabulary-tree-based approach, reducing complexity from $O(n^2)$ to $O(\log n)$. The images are then refined using the epipolar geometry constraints, which eliminate inconsistent matches by evaluating the geometric relationships between image pairs. After that, Bundle Adjustment refines camera poses and minimizes reprojection errors.

The workflow then proceeds to dense reconstruction using the PatchMatch Stereo algorithm. During this stage, depth values and surface normal vectors are estimated for each pixel across multiple images. The filtered depth maps are combined into a dense point cloud. The initial surface mesh is generated from this point cloud through Delaunay tetrahedralization combined with Max-Flow/Min-Cut optimization techniques. The resulting mesh is then smoothed with Laplacian filtering and decimated using Quadric Edge Collapse Decimation.

GLTF 2.0 format

GLTF 2.0 [18] was created by the Khronos Group specifically for efficient transmission of 3D models in web and VR applications. A GLTF model consists of a JSON descriptor referencing external binary geometry data (.bin) and texture images (.png). The JSON file has external references to the BIN and the PNG files, following the structure shown in Figure 2:

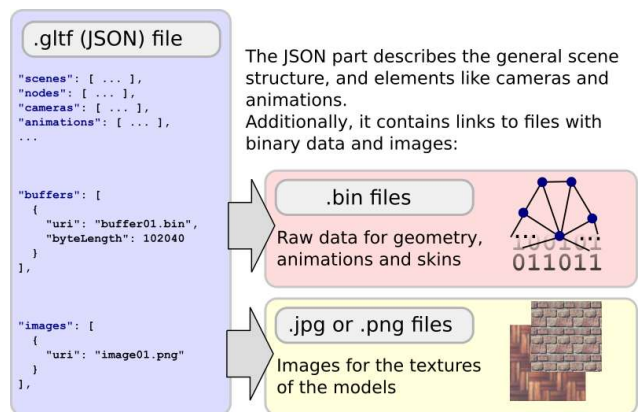


Figure 2. The structure of a GLTF model [18]

DESIGN AND IMPLEMENTATION

System architecture

The proposed solution offers an integrated end-to-end workflow for digitization and immersive visualization of

cultural heritage objects. It is built around the existing ChemiNova portal and organized into four components communicating over a Tailscale VPN mesh [19], ensuring stable connectivity regardless of the local network.

Data flows through the system as follows. The Android application authenticates the user against ChemiNova via JWT and sends captured images to the Flask server as multipart form-data. The Flask server initiates an asynchronous AliceVision reconstruction job and exposes status updates, which the application polls every ten seconds. Upon completion, the Android application downloads the generated GLTF, BIN, and PNG files and uploads them to ChemiNova through chunked binary transfer. The VR application authenticates independently against ChemiNova, retrieves the list of available 3D models, downloads the selected asset files, and loads them into the Unity scene using GLTFast. The four components of the system are:

- *Android application*: it serves as the entry point in the system. It allows the user to authenticate using the same credentials as in the ChemiNova portal, capture or select photographs and send them to the Flask server.
- *Flask server*: it is the bridge between the processing pipeline and the mobile application. It manages the states of the job and runs the pipeline as a subprocess. Upon completion, the Android application downloads the generated GLTF assets and uploads them to ChemiNova.
- *AliceVision pipeline*: it receives as input a set of overlapping pictures of the physical object and returns as output the GLTF model based on the desired detail level.
- *VR application*: it runs on the Meta Quest 2 headset. It was developed in Unity and communicates with the ChemiNova portal in order to retrieve the list of existing models and load them into the scene using GLTFast.

For a better overview of the system's architecture, a brief architectural diagram is shown in Figure 3:

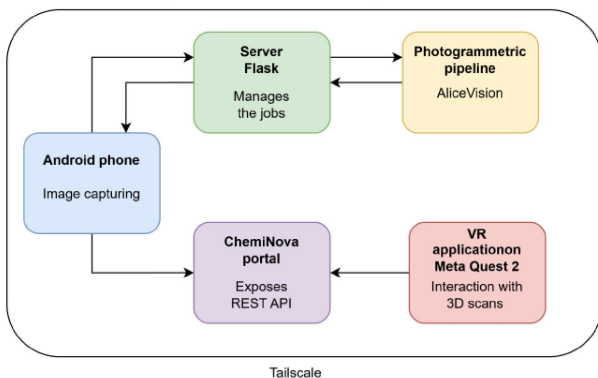


Figure 3. Architectural diagram of the system

Use cases

The system was designed to satisfy several key requirements and interaction scenarios, as follows:

- *Login/Register*: The users have access to the models if they create a new account in the ChemiNova portal, or log into an existing one.
- *Capturing the pictures*: The user is able to take pictures with the smartphone's camera, or select them from the gallery, and send them to the processing pipeline.
- *Monitoring the processing*: The user has access to the processing pipeline's real-time state, from the Android application.
- *Choosing the detail level*: The user can choose the level of detail of the generated model. There are 3 levels of detail: low (25k faces), mid (50k faces), and high (100k faces).
- *Visualization in VR*: The user can authenticate with the ChemiNova portal credentials in order to retrieve the list of existing models. Models can then be visualized, manipulated, and explored within the immersive virtual environment.

Photogrammetric pipeline

The main contribution of this system is the fully automated AliceVision pipeline. Upon receiving a collection of images, the pipeline executes every stage of the reconstruction process without requiring manual intervention, producing high-quality textured 3D models. The reconstruction workflow is executed as a subprocess and can be canceled at any time upon user request. Several computationally intensive stages, including Feature Extraction, Incremental Structure from Motion, Depth Map Estimation, Meshing, and Texturing, are configured to utilize NVIDIA GPU acceleration.

The pipeline undergoes a preprocessing step to resize the input images to a maximum of 3000px, on the longest side, and limit the dataset to 60 images to prevent GPU VRAM exhaustion. The images are selected through a uniform sampling strategy. This approach selects a representative subset of photographs that maintains complete coverage of the object while reducing processing requirements and reconstruction time. The steps are executed sequentially, as follows: CameraInit, FeatureExtraction, ImageMatching, FeatureMatching, StructureFromMotion, PrepareDenseScene, DepthMap, DepthMapFilter, Meshing, MeshFiltering and Texturing. Following reconstruction, a postprocessing step is applied. PyMeshLab is used to perform Laplacian smoothing and mesh decimation based on Quadric Error Metrics, ensuring that the final models have the desired level of quality. Since AliceVision tends to create multiple UDIM texture tiles, these textures are merged into one single texture atlas using the trimesh library. Finally, pygltflib library converts the resulted .obj output into a GLTF file.

VR application

The VR component is implemented as a Unity URP project and runs on the Oculus Meta Quest 2. Within the application, users can view the list of 3D models uploaded to the ChemiNova portal and interact with them. It communicates with the ChemiNova API to authenticate the users via JWT and retrieve the list of available 3D models. When the user selects a model, the associated GLTF, BIN, and PNG files are downloaded and loaded into the scene using the GLTFFast package. The XR Interaction Toolkit provides XRGrabInteractable components enabling users to grab, move, rotate, and scale objects using the controllers. Figure 4 depicts the list of 3D models and a model in the scene:



Figure 4. List of 3D models and model example

One last important aspect is how the user uses the controllers to interact with the models. For this, Table 2, contains the triggers and the events:

Trigger	Interaction description	Example Input/Output
Trigger button	UI Interaction and teleportation	Input: Index finger press.
		Output: A raycast is emitted to select UI panels or to set a teleportation target area.
Grip button	Grab, inspect and scale objects	Input: Middle finger press.
		Output: The 3D model anchors to the user's virtual hand, allowing them to pick it up, inspect it closely, and scale it using a two-handed pulling gesture.
Joystick	Locomotion and scene navigation	Input: Thumb tilt.
		Output: Smooth continuous movement through the virtual environment or snap turning to adjust the viewing angle.

Table 2. Controllers' triggers

Android application

The Android application represents the component responsible for image acquisition and reconstruction management. It was implemented using Kotlin, with Jetpack Compose for the UI, following the Model-View-ViewModel (MVVM) architectural pattern. Retrofit was used for communication with the Flask server and the ChemiNova portal.

To initiate a reconstruction, users are required to capture a minimum of three images and choose a desired quality level. The selected data is then uploaded to the Flask server, which initiates the reconstruction process. The application interrogates the server every ten seconds to check the processing status. This mechanism also enables users to cancel active reconstruction jobs at any stage. Upon completion, the users are redirected to the 3D viewer screen, supported via SceneView library, where they can see a preview of the generated 3D GLTF model, before uploading it to the ChemiNova portal.

Two of the most important screens of the application are the ViewerScreen and NewScanScreen, shown in Figure 5:

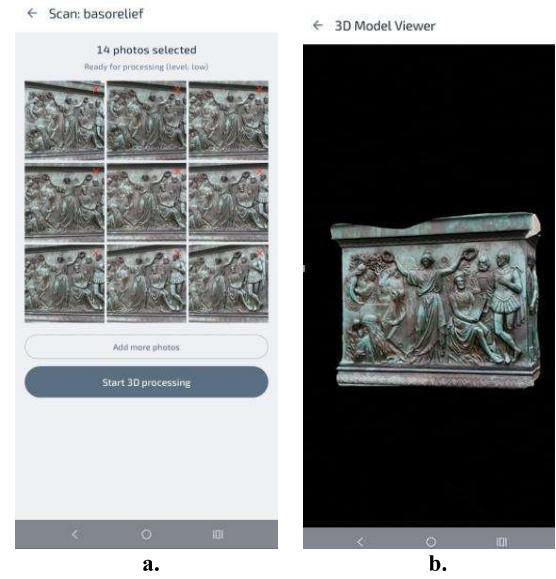


Figure 5. NewScanScreen (a) and ViewerScreen (b)

TESTING AND RESULTS

The proposed system was evaluated from both functional and non-functional perspectives. Testing was performed using multiple image datasets containing objects of different shapes, sizes, and surface characteristics. Both the number of input images and the selected levels of detail were varied across runs. The evaluated datasets include custom smartphone captures (the cat object) and open-source datasets from AliceVision/Meshroom (the bas-relief and tree trunk), ensuring the reproducibility of the results.

Pipeline testing

The initial results show that the processing times are highly dependent on the number of images and selected quality. First example depicts the total processing times for a data set of 50 images processed at the highest quality and then for 25 images processed at the lowest quality. The processing times from Table 3 reflect a single typical run for each dataset.

Object	Nb. images	Quality level	Total processing time(s)
Cat object	50	High 100k faces	684.7s
Cat object	25	Low 25k faces	296.5s

Table 3. Total processing times for different inputs

To verify that the generated models contained the intended number of faces, the resulting meshes were imported into Blender and inspected manually, as can be seen in Figure 6. To the right is the most detailed model, as on the left side is the least detailed model.

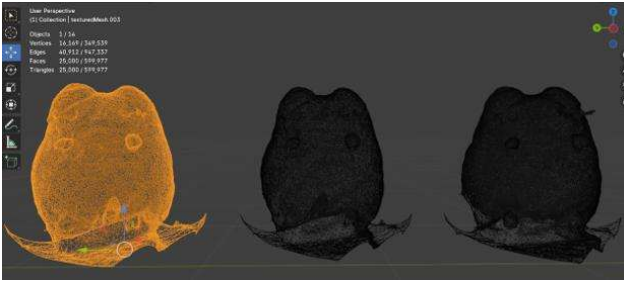


Figure 6. Checking the number of faces in Blender

All of these were tested on a Lenovo LOQ 15AHP10, equipped with an AMD Ryzen 7 processor, 32GB RAM, and an NVIDIA GeForce RTX 5060 GPU.

A more detailed examination of the pipeline was performed to determine the execution time of each reconstruction stage and determine the most time-consuming steps. In this regard, Table 4, shows the processing times for a data set of 50 images.

Step	Time(s)
CameraInit	0.5s
FeatureExtraction	13.0s
ImageMatching	0.5s
FeatureMatching	146.5s
StructureFromMotion	198.1s
PrepareDenseScene	20.6s
DepthMap	122.1s
DepthMapFilter	58.7s
Meshing	59.6s
MeshFiltering	3.5s

Texturing	61.6s
Total	684.7s

Table 4. Processing times for each step

Additional experiments were performed using photographs captured with professional cameras, including a bas-relief and a tree trunk. Results are shown in Table 5:

Object	Nb. images	Quality level	Total processing time(s)
Bas-relief	14	High 100k faces	472s
Bas-relief	7	Low 25k faces	153.6s
Tree trunk	41	High 100k faces	1376.4s
Tree trunk	6	Low 25k faces	93.6s

Table 5. Processing times for objects photographed with professional cameras

Model quality and file sizes

An increase in reconstruction quality inevitably leads to larger file sizes due to higher number of faces used to represent geometric details. To assess this relationship, models generated at different quality levels were compared.

Model quality was assessed by visual comparison against the physical objects, examining surface detail reproduction, color fidelity, and geometric completeness. For opaque objects with rich surface textures, the reconstructed meshes accurately reproduced surface detail, color distribution, and overall geometry. Transparent or reflective objects produced models with artifacts and holes in the mesh, as SfM algorithms struggle to match feature points on surfaces lacking distinct texture. Figure 7 shows a representative comparison between the 3D scan and the physical object for an opaque, well-textured artifact that is suitable for SfM reconstruction.

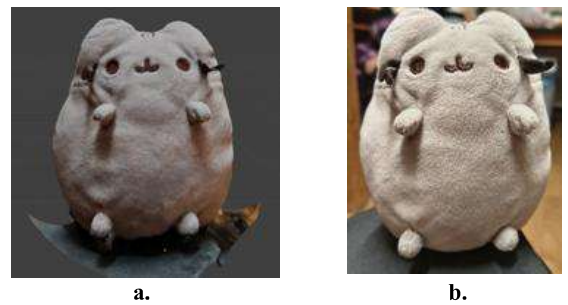


Figure 7. 3D scan of the object (a) and the physical object (b)

Further testing showed that the model size increases proportionally with faces count. Results are recorded in Table 6. The object for which these results were recorded is the one shown in the previous image.

Quality level	Nb. of faces	Size (Mb)
High	100.000	7.57Mb
Mid	50.000	3.80Mb
Low	25.000	1.89Mb

Table 6. Size of models for different quality levels

VR performance

To test the VR application's performance, the OVR Metrics Tool [20], available on the Meta Quest 2 app store, was used to record metrics such as FPS, GPU time and CPU usage. It tracked how these metrics fluctuated based on user actions and the complexity of the loaded models. Upon testing the same model as above, at different quality levels, some differences in performance can be observed. Table 7, and Figure 8 compare these metrics.

Metrics	Low 25k faces	High 100k faces
FPS	90	87
CPU Utilization	30	33
GPU Utilization	93	91

Table 7. VR performance comparison based on model quality

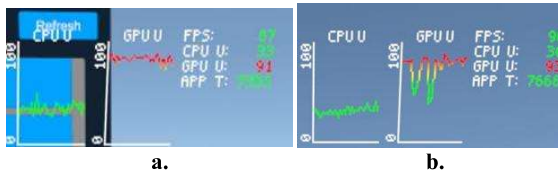


Figure 8. Performance metrics of a low-quality model (a) and a high-quality model (b)

User study

A formal user study evaluating usability and perceived immersion was conducted. It involved four students who tested the whole system and their feedback was captured through a questionnaire with 7 questions, which are presented in Table 8:

Question	Number of responses	Conclusions
1. How intuitive did you find the mobile app	4	Very easy to use

interface?		
2. How easy did you find it to take photos of the objects and send them for processing?	2	5/5: Very easy
	2	4/5: Easy
3. How satisfied were you with the waiting time? Did you feel you waited too long to receive the 3D model?	1	5/5: Very satisfied
	2	4/5: Satisfied
	1	3/5: Acceptable
4. How satisfied are you with the quality of the resulting models?	3	5/5: Very satisfied
	1	4/5: Satisfied
5. How natural did the interaction with the model in VR feel to you?	2	5/5: Very natural
	1	4/5: Natural
	1	3/5: Acceptable
6. Did you encounter any connectivity issues while using the application?	4	Not at all
7. Would you recommend this system for the digitization and visualization of cultural heritage objects?	3	5/5: Surely yes
	1	4/5: Yes

Table 8. Feedback questionnaire with the answers from the students

The results show overall positive feedback, with room for improvements in future iterations.

CONCLUSION

The primary contribution of this work was the development of a complete phone-to-VR workflow. The proposed system integrates image acquisition, automated 3D reconstruction, digital asset management, and immersive visualization within a unified ecosystem. As shown in Table 1 from the Related Work section, no existing solution covers the complete workflow from mobile capture to institutional storage and immersive VR visualization within a single open-source platform. The present system fills this gap. The system automatically reconstructs textured 3D models through a photogrammetry pipeline, allows users to preview the generated models on a mobile device, stores them within the ChemiNova platform, and finally makes them available for immersive visualization on the Meta Quest 2 headset. As a result, users can seamlessly transition from physical object capture to interactive virtual exploration without requiring specialized technical knowledge. Experimental results demonstrate that the proposed solution

is capable of generating visually accurate 3D representations while maintaining acceptable processing times and storage requirements. Performance evaluations confirmed that generated assets can be visualized and manipulated smoothly in VR across all three quality levels.

Future work will explore cloud deployment to remove the dependency on a local processing laptop, and the integration of machine learning techniques to improve reconstruction quality for reflective or low-texture objects.

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