Digital Preservation and Augmented Reality for Historical Surveying Instruments: A Photogrammetric Approach to Cultural Heritage Documentation

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Abstract

Historical surveying instruments represent invaluable cultural heritage artifacts that embody centuries of scientific and technological advancement in geodesy and cartography. However, their inherent fragility and limited accessibility restrict their educational potential and preservation. This study proposes an integrated digital preservation methodology for the Cartographic Sciences Museum at the Federal University of Pernambuco (UFPE), combining low-cost smartphone photogrammetry, three-dimensional reconstruction, geometric optimization, and augmented reality (AR) visualization. A Structure-from-Motion (SfM) workflow processed 303 smartphone images (Xiaomi Poco F5 Pro) with systematic multi-angular capture and controlled overlap (30-60%). A three-chunk processing strategy in Agisoft Metashape optimized computational efficiency while maintaining geometric consistency. Post-processing in Blender reduced polygon complexity by 90% while preserving critical morphological features. Metric validation achieved root mean square error (RMSE) of 0.42 cm, demonstrating geometric fidelity adequate for heritage documentation. Integration into an AR application (Unity/Vuforia) enabled interactive mobile visualization of digitized artifacts. This methodology democratizes access to the UFPE collection for academic research and public engagement, enabling students, researchers, and the general public to explore historical geodetic instruments interactively. Results demonstrate that accessible, low-cost technologies can achieve quality comparable to conventional surveying methods while advancing digital heritage preservation and science communication.

1. Introduction

Cultural heritage, in its various forms, represents a fundamental link to the past, providing insights into the evolution of society, science, and technology. Among valuable cultural assets, historical instruments of topography and geodesy stand out due to their scientific and technological relevance, representing milestones in the development of cartographic sciences. However, the preservation of these artifacts faces significant challenges, mainly due to their fragility, susceptibility to environmental degradation, and handling complexity, which restricts access for study and dissemination purposes (Aicardi et al., 2018; Duester et al., 2023).

Three-dimensional (3D) digitization has emerged as a promising solution for the documentation and preservation of such assets, allowing the creation of virtual replicas that can be accessed and studied without risking damage to the original objects. The reconstruction process is grounded in principles of photogrammetric computer vision, particularly in Structure-from-Motion approaches (Förstner and Wrobel, 2016). Traditionally, high-precision digitization requires expensive and specialized equipment, such as terrestrial laser scanners, which limits its application in institutions with restricted budgets. Close-range photogrammetry, particularly when performed using low-cost devices such as smartphones, represents a viable and accessible alternative for generating detailed 3D models (Yilmazturk and Gurbak, 2019; Mohareb et al., 2023).

In parallel, Augmented Reality (AR) has been increasingly adopted as a powerful tool for interacting with digital 3D models, offering immersive and interactive experiences that enhance education and scientific dissemination (Gong et al., 2022; Spallone, 2022). The combination of low-cost photogrammetry and AR enables not only digital preservation of cultural heritage but also democratizes access, making these assets available to a broader audience through mobile devices.

This study proposes an integrated methodology for the digital preservation of historical topographic and geodetic instruments using smartphone-based photogrammetry and augmented reality. The objective is to develop a complete pipeline, from image acquisition to interactive AR visualization, that is accessible and capable of producing high-fidelity 3D models. The methodology was applied to four historical instruments from the collection of the Museum of Geodetic and Cartographic Sciences at the Federal University of Pernambuco (UFPE), including a Wild T2 theodolite, aiming not only to preserve the artifacts but also to promote the scientific and technological heritage of the institution for the academic community and the general public.

2. Methodology

This study adopts an integrated photogrammetric workflow for the digital preservation of historical surveying instruments. The methodology consists of four main stages: image acquisition, photogrammetric processing, model optimization, and augmented reality integration. The workflow was designed to ensure geometric consistency, computational efficiency, and compatibility with mobile visualization environments.

2.1 Image Acquisition and Chunk Organization

The object selected for this study is a Wild T2 theodolite (No. 21200), a historical surveying instrument belonging to the Cartographic and Geodetic Sciences Museum of the Federal University of Pernambuco (UFPE). The museum hosts a significant collection of scientific instruments that contributed to the development of topography, geodesy, astronomy, photogrammetry, and cartography in Brazil. This collection represents an important technical and scientific heritage, serving as a valuable resource for research, education, and digital preservation initiatives.

Due to its complex geometry, metallic surfaces, and fine mechanical components, the selected theodolite represents a suitable case study for evaluating close-range photogrammetry using low-cost imaging devices. These characteristics present common challenges for photogrammetric reconstruction, such as reflections, occlusions, and limited texture areas, making the object particularly relevant for methodological assessment.

Image acquisition was performed using a Xiaomi Poco F5 Pro smartphone, equipped with a camera resolution of 3000 × 3000 pixels, approximate focal length of 6 mm, aperture f/1.9, and exposure time of 1/60 s. A total of 303 images were captured following a circular acquisition strategy around the object, ensuring adequate overlap and multi-angular coverage for the photogrammetric reconstruction workflow. Part of this strategy has been recommended by (Yilmazturk & Gurbak, 2019; Asadpour, 2021).

To improve geometric coverage and minimize occlusions, three circular acquisition rings were performed at different heights and viewing angles around the instrument. This multi-ring acquisition strategy enhances reconstruction strength and improves the representation of complex surfaces. Additionally, a 10 cm scale bar was positioned near the object during image acquisition to enable metric scaling during the photogrammetric processing workflow (Farella et al., 2022). The image acquisition strategy adopted in this study is illustrated in Figure 1.

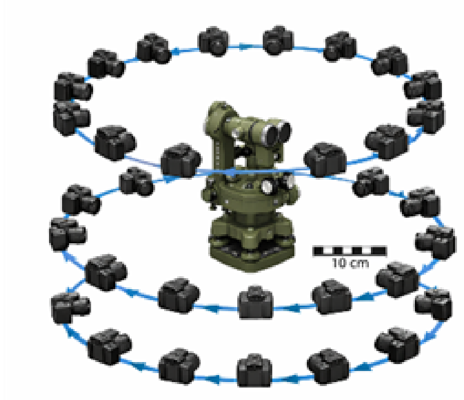

Figure 1. Shows the circular acquisition strategy adopted for the Wild T2 theodolite.

The 303 images were organized into three distinct chunks to improve geometric coverage and minimize occlusions. The acquisition protocol consisted of three complete circular trajectories (360°) around the theodolite, with an approximate inclination of 30° relative to the horizontal plane, ensuring multiple viewing angles and improved surface representation. Image overlap was maintained between 30% and 60%, which is a critical factor for reliable phototriangulation and Structure-from-Motion reconstruction. The chunk strategy was defined as follows:

- Chunk 1: 120 images captured with horizontal smartphone orientation, focusing on the upper portion of the instrument (dome) and ensuring adequate coverage of the top geometry.
- Chunk 2: 68 images captured with vertical orientation, covering the intermediate section of the theodolite.
- Chunk 3: 115 images captured with vertical orientation, focusing on the opposite side and base of the instrument, complementing the coverage of Chunk 2.

The combination of horizontal and vertical orientations improved geometric coverage and reduced potential occlusions, particularly in areas with complex geometry. This multi-ring acquisition strategy enabled comprehensive coverage of all surfaces of the theodolite, including areas with limited accessibility and fine structural details. The spatial distribution of the three acquisition rings is illustrated in Figure 2, 1st is Chunk 1 - upper ring with horizontal orientation, 2nd is Chunk 2 - intermediate ring with vertical orientation, and 3rd Chunk 3 - lower ring with vertical orientation.

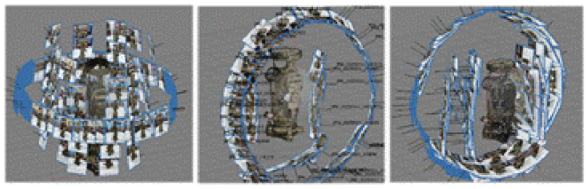

Figure 2. Camera distribution for 3 circular acquisition rings around the Wild T2 theodolite.

All image acquisition was conducted under controlled lighting conditions using diffuse illumination sources. This approach minimized cast shadows, abrupt variations in light intensity, and specular reflections caused by metallic surfaces, which could otherwise compromise feature detection and image matching during the Structure-from-Motion reconstruction.

A scale reference of 10 cm is also visible in the acquisition setup (Figure 3), providing a visual basis for subsequent metric scaling of the reconstructed model.

Figure 3. Scale bar positioned near the Wild T2 theodolite during image acquisitions.

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2.2 Photogrammetric Processing Workflow

The photogrammetric processing was performed using Agisoft Metashape Professional (version 2.2.1), following a Structure-from-Motion (SfM) workflow for three-dimensional reconstruction of the Wild T2 theodolite. The processing workflow consisted of image alignment, chunk merging, scale-constrained optimization, dense point cloud generation, mesh reconstruction, and texture mapping.

Initially, the images from each chunk were aligned independently to estimate camera positions and generate sparse point clouds. This strategy improves matching strength and reduces possible alignment errors, particularly in objects with complex geometry and reflective surfaces. The alignment process was based on automatic feature detection and matching, followed by bundle adjustment to refine camera parameters.

After the individual alignment of the three chunks, the datasets were merged into a single project and globally optimized. This step ensured geometric consistency across the complete dataset and improved overall reconstruction stability. This approach allowed for efficient processing of the large number of images while maintaining high accuracy (Jasińska et al., 2023).

Following chunk merging, the scale bar introduced during image acquisition (Figure 3) was incorporated into the photogrammetric workflow. The endpoints of the scale bar were manually identified in multiple images, and the known distance of 10 cm was assigned within Agisoft Metashape. This procedure enabled metric scaling of the reconstructed model and improved dimensional consistency prior to dense reconstruction.

Subsequently, camera parameters were optimized to minimize reprojection errors and refine the photogrammetric solution. After optimization, a dense point cloud was generated, providing a detailed representation of the object's geometry.

From the dense point cloud, a triangular mesh was generated to create a continuous surface representation of the theodolite. Texture mapping was then performed by projecting radiometric information from the original images onto the reconstructed mesh, resulting in a realistic three-dimensional model. The final reconstructed model generated in Agisoft Metashape is illustrated in Figure 4.

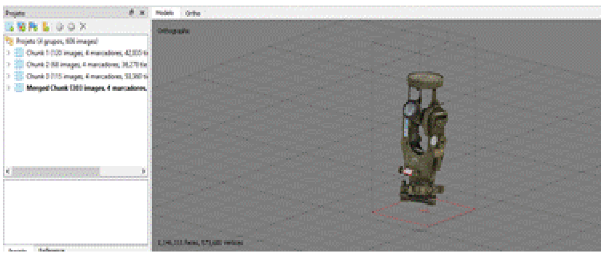

Figure 4. Final Metashape 3D model reconstructed

Following the reconstruction and texturing stages, the three-dimensional model was exported from Agisoft Metashape in FBX format. This format was selected due to its compatibility with external 3D modeling environments and its ability to preserve geometric and texture information. The exported model was subsequently imported into Blender for further post-processing, including mesh refinement, noise removal, and polygon optimization, as described in Section 2.3.

2.3 Model Optimization

The reconstructed model was imported into Blender for geometric refinement and optimization. Blender is an open-source 3D modeling platform widely used for visualization, mesh editing, and optimization of three-dimensional datasets derived from photogrammetric workflows. Its open-source nature promotes reproducibility and accessibility, which are important aspects in scientific and educational applications (Blender Online Community, 2023).

The mesh was initially inspected to identify reconstruction artifacts and geometric inconsistencies generated during the photogrammetric reconstruction process. The refinement activities included topological cleaning, with removal of spurious geometries and artifacts originating from the reconstruction stage, as well as correction of mesh inconsistencies, such as non-manifold elements and irregularities in triangulation. These procedures improved geometric consistency and overall model quality.

Subsequently, mesh refinement operations were applied, including smoothing procedures and local adjustments to improve surface continuity while preserving geometric details of the instrument. This step was particularly important for areas with complex geometry and fine structural elements.

To improve computational efficiency and enable real-time visualization, polygon reduction techniques were applied to decrease mesh complexity while maintaining essential geometric features. This optimization is especially relevant for interactive visualization environments and augmented reality applications, where model performance is critical. The optimized three-dimensional model generated in Blender is illustrated in Figure 5.

Figure 5. Optimized 3D model of the Wild T2 theodolite after mesh refinement and polygon reduction performed in Blender.

2.4 Augmented Reality Integration and Visualization Workflow

For the visualization of the models in an Augmented Reality (AR) environment, a mobile application was developed using the Unity game engine (version 2020.3.14f1) (Unity Technologies, 2024) in combination with the Vuforia Engine (version 11.4), widely used in computer vision-based AR systems (Omaia and Machado, 2020; PTC Inc., 2024).

Following mesh optimization in Blender, the refined three-dimensional model was prepared for augmented reality visualization. The optimized model was exported from Blender in FBX format, ensuring compatibility with real-time visualization platforms while preserving geometric and texture information. Subsequently, the model was imported into the Unity development environment, which was used as the visualization platform for the augmented reality application.

The development process included configuration of the project environment in Unity, integration and activation of the Vuforia SDK, insertion of the license key, and definition of image targets used as markers for tracking and anchoring virtual content in the physical environment. Vuforia provides image-based tracking capabilities, allowing virtual models to be superimposed onto real-world scenes using mobile devices.
After defining the tracking parameters, the previously generated three-dimensional models were imported and positioned within the virtual environment and associated with the corresponding image targets to enable real-time visualization and interaction. The integration architecture was designed to allow users to visualize and explore 3D models linked to the museum objects directly through mobile devices, promoting an interactive and intuitive interface.

The final augmented reality visualization enabled interactive exploration of the three-dimensional model, allowing users to observe the instrument from multiple perspectives and analyze geometric details in an immersive environment. The augmented reality application developed for visualization of the reconstructed model is illustrated in Figure 6.

Figure 6. Augmented reality visualization of the optimized Wild T2 theodolite model using Unity and Vuforia

3. Results and Discussion

3.1 Mesh Optimization Results

After photogrammetric reconstruction, the three-dimensional model was optimized in Blender using the Decimate modifier to reduce mesh complexity and improve computational performance. Subsequently, the Decimate modifier was applied in Blender with a reduction factor of 0.1, resulting in approximately 57,877 vertices and 114,575 faces, corresponding to a reduction of about 90% in geometric complexity.

The reduction factor of 0.10 was selected as it provided the best balance between geometric simplification and preservation of important structural details of the theodolite. This choice allowed a significant reduction in mesh complexity while maintaining the main morphological characteristics and dimensional consistency of the object.

The comparison between the original and simplified models demonstrated that, despite the substantial reduction in the number of polygons, the main morphological features were preserved. This step proved to be essential for balancing visual quality and computational performance, particularly for applications on mobile devices.

The results of the geometric simplification are presented in Table 1, which shows the reduction in the number of vertices, edges, and faces after applying the Decimate modifier.

Decimate	Before	After
Objects	1/6	1/6
Vertices	573,467	57,877
Edges	1,718,626	171,856
Faces	1,145,755	114,575
Triangles	1,145,755	114,575

Table 1. Number of polygons of the 3D mesh before and after applying the Decimate modifier.

This reduction significantly improves model performance for real-time applications without compromising the geometric integrity of the reconstructed instrument.

3.2 Metric Validation of the 3D Model

To evaluate the geometric accuracy of the reconstructed model, a quantitative analysis was conducted by comparing measurements obtained directly from the physical object with corresponding measurements extracted from the digital model. Five characteristic dimensions of the Wild T2 theodolite were selected for evaluation. The comparison results are presented in Table 2.

Dimensions	Physical Object (cm)	Digital Model (cm)
Height	30.5	29.955
Width	11.5	11.4923
Diameter (compass)	9.5	9.45417
Distance (between lateral screws)	10.5	10.578
Base dimension	10.0	10.7642

Table 2. Comparison between physical object measurements and digital model dimensions.

Based on these measurements, the Root Mean Square Error (RMSE) was calculated, resulting in an approximate value of

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0.42 cm. Considering the analyzed dimensions, this value corresponds to a relative error ranging from approximately 1.5% to 4%, indicating good agreement between the reconstructed model and the physical object.

This level of error is consistent with results reported in the literature for smartphone-based photogrammetry (Yilmazturk & Gurbak, 2019; Jasińska et al., 2023). These findings demonstrate that, even when using a low-cost photogrammetric workflow and a scale constraint based on visual reference, the reconstructed model presents satisfactory dimensional consistency.

The results indicate that the generated model is suitable for applications involving digital documentation, interactive visualization, and integration into augmented reality environments.

3.3 Augmented Reality Visualization

In addition to the digitization and refinement of the three-dimensional models, this study incorporated Augmented Reality (AR) as a technological approach for exhibition, preservation, and analysis of the museum collection. AR visualization enables the superimposition of virtual three-dimensional objects onto the physical environment in real time using mobile devices such as smartphones and tablets.

In the context of the Museum of Geodetic and Cartographic Sciences at UFPE, the application of this technology enabled visualization of digital replicas at real scale, anchored to physical supports or visual markers positioned within exhibition showcases. This approach enhanced the museum experience by making the collection more accessible, interactive, and informative.

Furthermore, the use of AR contributed to reducing direct handling of original instruments, which is particularly important for historical and sensitive objects. This approach supports conservation strategies by minimizing physical contact while still allowing detailed exploration of the artifacts.

From an academic perspective, AR also enabled detailed visual analysis of the reconstructed models. Users were able to inspect the three-dimensional representations in real time, navigating around the objects and observing geometric features from multiple viewpoints. This capability facilitates understanding complex geometries and supports educational and research activities.

The integration of augmented reality into the digital workflow also demonstrated the potential of immersive technologies for heritage preservation and knowledge dissemination. By combining photogrammetry, mesh optimization, and AR visualization, the proposed workflow provides an accessible and efficient approach for digital documentation of scientific instruments. The AR visualization of the reconstructed Wild T2 theodolite is presented in Figure 7.

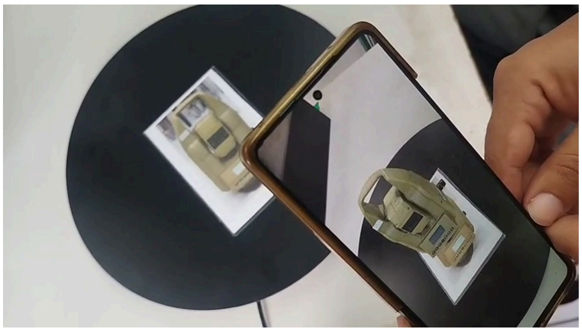

Figure 7. Augmented reality visualization T2 allowing interactive exploration of the reconstructed model in a real-world environment.

4. Conclusion

This study presented a complete workflow for the digital reconstruction and visualization of a historical geodetic instrument using close-range photogrammetry, mesh optimization, and augmented reality technologies. The proposed methodology demonstrated that low-cost image acquisition using a smartphone, combined with photogrammetric processing and open-source tools, can generate accurate and visually consistent three-dimensional models suitable for digital preservation and interactive visualization.

The multi-ring acquisition strategy and scale bar integration enabled reliable geometric reconstruction of the Wild T2 theodolite. The metric validation showed satisfactory dimensional consistency, with an RMSE of approximately 0.42 cm and relative errors ranging between 1.5% and 4%, indicating good agreement between the reconstructed model and the physical object. Additionally, mesh optimization using Blender with a reduction factor of 0.10 significantly reduced polygon complexity while preserving the main morphological characteristics of the instrument.

The proposed workflow was applied to four historical instruments from the Museum of Geodetic and Cartographic Sciences at UFPE, which were successfully digitized and documented. The integration of the optimized models into an augmented reality environment enabled interactive visualization and exploration of the reconstructed instruments.

During guided visits to the museum, the augmented reality application demonstrated strong potential for educational and outreach activities. Visitors were able to interact with digital replicas, enhancing engagement and understanding while reducing direct handling of original artifacts, contributing to their physical preservation.

Overall, the results demonstrate that the integration of close-range photogrammetry, open-source modeling tools, and augmented reality provides an efficient and accessible approach for digital documentation, preservation, and dissemination of scientific heritage. Future work includes expanding the methodology to additional instruments and further evaluating educational and user interaction aspects. Regarding the development of the integrated digital system, its implementation not only enables structured management of the museum collection but also facilitates access to information and contributes to the preservation of institutional technical heritage. Furthermore, it promotes a museum experience aligned with contemporary demands for accessibility, interactivity, and the integration of digital technologies.

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