Reconstruction of Archaeological Sites Using Aerial Photogrammetry

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ABSTRACT

Photogrammetry is a technique that uses overlapping photographic images taken from different vantage points to extract 3D geometric data and generate accurate 3D models. In archaeology, photogrammetry is revolutionizing the recording and analysis of excavations, artifacts, and historic sites. This paper examines the use of aerial photogrammetry with unmanned aerial vehicles (UAVs) to reconstruct archaeological sites in 3D. A background on photogrammetry principles and techniques is provided. The paper then focuses on a case study using aerial and terrestrial photogrammetry data of a 16th century Portuguese fort in Kilwa Kisiwani, Tanzania to generate a 3D model. Photographs were processed with RealityCapture photogrammetry software. The 3D model was further refined in SketchUp modeling software and methods for future developments are discussed. Results demonstrate that aerial photogrammetry is an accurate, efficient, and cost-effective approach for 3D reconstruction and analysis of archaeological sites compared to other techniques. The highly detailed spatial data can help archaeologists digitally preserve sites, analyze changes over time, quantify measurements, visualize former structures, and create interactive environments for education and research.

Keyword: - *Photogrammetry, Aerial photogrammetry, UAV photogrammetry,Archaeological site reconstruction, 3D modeling, RealityCapture, SketchUp, Kilwa Kisiwani and Tanzania.*

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1. Reconstruction of Archaeological Sites Using

Aerial Photogrammetry

Archaeology is the study of past human societies through the analysis of material remains left behind by ancient peoples (National Geographic Society, n.d.). These remains include artifacts like tools, jewelry, and pottery as well as features like graves, buildings, and garbage dumps. Archaeologists excavate sites and analyze these objects to understand aspects of past cultures such as economy, social organization, technology, art, and belief systems. A major challenge is that sites are buried under layers of soil, sand, or debris over hundreds or thousands of years. Remote sensing technologies like aerial photography, satellite imagery, radar, and lidar allow archaeologists to detect sites and map surface and subsurface features without excavation (Society for American Archaeology, 2015).

Once sites are located, a primary task is to accurately record all artifacts, structures, and spatial relationships from the excavation. Traditional methods involve simple photography, hand drawings, written notes, and basic measurement tools. However, these techniques are limited in capturing the full 3D context of a site. Photogrammetry has now become a standard method in archaeology for recording and analyzing excavations in 3D. The basic principle is to take overlapping photographic images from different locations around a site or object, and then use specialized computer software to extract 3D coordinates and generate point clouds, meshes, and 3D models (Mathys et al., 2019).

Photogrammetry can utilize ground-based cameras for small artifacts or handheld cameras for mapping building interiors and small excavation trenches. However, capturing entire excavation sites, large structures, or cultural landscapes requires aerial photogrammetry. Historically this was done with manned aircraft but unmanned aerial vehicles (UAVs) are now preferred for flexibility, cost savings, and safety (Bisson-Larrivée & LeMoine, 2022). Aerial photography from UAVs provides comprehensive high-resolution data to record sites and create detailed 3D visualizations. The 3D models aid in site mapping, measurement, analysis of changes over time, reconstruction of former structures, and interactive experiences through augmented or virtual reality.

This paper examines the use of aerial photogrammetry to digitally reconstruct archaeological sites in 3D. A background on photogrammetry principles and techniques is first reviewed. The paper then focuses on a case study utilizing aerial and terrestrial photogrammetry data of a 16th century Portuguese fort located in the Kilwa archipelago of Tanzania to generate a 3D model. The model was further refined through 3D modeling software. The case study demonstrates an end-to-end workflow for accurate 3D capturing and reconstruction of archaeological sites through aerial photogrammetry.

1.1 Photogrammetry Principles and Techniques

Photogrammetry is defined as "the science of making measurements from photographs" (ScienceDirect, 2012, para. 1). While the principles of projective geometry were experimented with as early as the 15th century, photogrammetry emerged as a quantitative measurement technique with aerial photography in the 19th century (Mathys et al., 2019). The basis of photogrammetry is triangulation. By taking photographs from at least two different locations, the parallax shifts of reference points between the images allow for precise triangulation of 3D coordinates of surface points on the subject. The below figure illustrates this concept. Modern digital photogrammetry software automates this process by identifying common points between overlapping images and creating dense point clouds through bundle adjustment algorithms. The more reference images taken from different positions with a high degree of overlap, the more accurate the triangulation. Photogrammetry can determine 3D locations down to a fraction of a pixel. The point clouds are then turned into polygonal mesh models, and detailed color textures mapped from the photograph pixels onto the model surface (Mathys et al., 2019). The types of photogrammetry are generally categorized based on the camera position used. The two main divisions are aerial photogrammetry where the camera is airborne, and terrestrial (close-range) photogrammetry where the camera is ground-based (ScienceDirect, 2012).

1.2 Aerial Photogrammetry

In aerial photogrammetry, the camera is mounted on an aircraft or UAV and captures photographs from above. Aerial photogrammetry emerged in the 19th century using kites, balloons, pigeons, and rockets to lift cameras aloft, but manned fixed-wing aircraft became the standard platform in the 20th century. Aerial photography revolutionized mapping, military reconnaissance, and archaeology. Overlapping vertical photos could be used to create topographic maps, measure distances and areas, and discover archaeological sites not visible from the ground. Stereo-plotters enabled photos to be viewed in 3D to create digital elevation models as well (ScienceDirect, 2012). Today, UAVs offer several advantages over manned aircraft for aerial photogrammetry. UAVs can be deployed on demand, flown lower and slower, require less airspace regulation, and capture data with higher image resolution and accuracy. Common UAV platforms include multi-rotors like quadcopters and fixed wing systems UAVs can also utilize a variety of sensors beyond basic RGB cameras, including multi/hyper-spectral, thermal, and lidar. The ability to fly low and slow with UAVs enables comprehensive photography of excavation sites down to centimeter resolution. Photogrammetry technique. For 3D modeling, nadir (vertical) aerial photos are combined with oblique angle photos captured by orbiting the site. The image overlap should be 60-80% between flight lines. Key parameters that affect model accuracy include flight altitude, camera specifications like sensor size and lens attributes, number of reference images, and the distribution of camera locations surrounding the subject (Mathys et al., 2019).

1.3 Terrestrial Photogrammetry

In terrestrial or close-range photogrammetry, the camera positions are ground-based. Applications include surveying and modeling buildings, industrial structures, accident sites, small artifacts, and archaeological excavations. Terrestrial photogrammetry utilizes normal handheld or tripod mounted cameras rather than specialized metric cameras. Photos are taken from multiple viewpoints around the subject with adequate overlap for 3D triangulation. Image-based modeling software processes the photos into dense 3D point clouds and meshes usable for measurement and modeling purposes (ScienceDirect, 2012). In archaeology, terrestrial photogrammetry is ideal for small artifacts, graves, architectural elements, and excavation pits where getting aerial photos is impractical. Photos can be captured simply by walking around the subject. For large sites, terrestrial and aerial photogrammetry are complementary. The aerial photos provide the overall site context, while terrestrial fills in details at ground level. Laser scanning is an alternative to terrestrial photogrammetry which directly sweeps structures with a lidar beam to map geometries (Elkhrachy, 2021). Photogrammetry can provide higher resolution textures combined with lidar scans.

2. Creating 3D Models

Introduction The standard workflow for generating 3D models through photogrammetry consists of the following stages:

1. Capture - Acquire photography from suitable camera positions around the subject with adequate overlap.
2. Align photos - Photogrammetry software detects common points between photos and matches them.
3. Build point cloud - Software calculates 3D coordinates for points based on triangulation of matched points.
4. Generate mesh - A polygonal mesh is constructed by connecting the point cloud.
5. Texture mapping - Color information from photos is projected onto the mesh to create a textured model.
6. Export - The 3D model can be exported to various formats for further applications.

(Bisson-Larrivée & LeMoine, 2022)

There are numerous commercial and open-source photogrammetry software options. Example packages include RealityCapture, Agisoft Metashape, 3D Zephyr, Pix4D, DroneDeploy, Open Drone Map, Visual SFM, and Meshroom. The software continues to improve in computational processing power and capabilities for large datasets. Key factors in software choice include processing speed, scalability, supported input formats and outputs generated, automation and ease of use, and cost. The final 3D model can be utilized as is for measurement and analysis in dedicated photogrammetry or GIS software, or exported to 3D modeling packages for additional refinements and applications. The model accuracy depends on various elements like camera optics, network geometry, reference scale, and ground control points (Mathys et al., 2019). But in general, photogrammetry can achieve survey-grade precision at less cost than traditional methods. The wealth of spatial data provided by photogrammetry has vast applications across diverse fields including archaeology, architecture, engineering, construction, industrial design, forensics, and entertainment.

2.1. Kilwa Kisiwani Fortress Case Study

To demonstrate a real-world application of photogrammetry for archaeological 3D modeling, this case study examines the modeling of a 16th century Portuguese fortress located on Kilwa Kisiwani island off the coast of Tanzania. Kilwa Kisiwani was a major medieval Swahili port city and UNESCO World Heritage site (Almukhtar et al., 2021). The fortress was constructed by the Portuguese after their conquest of Kilwa in 1505 CE and served as the center of Portuguese control in the region for nearly a century. It is an excellent example of early European colonial architecture in sub-Saharan Africa. However, the fortress has deteriorated from centuries of abandonment and coastal weathering. Photogrammetry was utilized to digitally preserve its current state for research and education purposes. The 3D modeling data was obtained from openheritage3d.org, a nonprofit aggregator of spatial data on cultural heritage sites (Almukhtar et al., 2021). It includes 25 GB of aerial photographs captured via UAV and 25 GB of terrestrial photographs of the fortress exterior and interior spaces. The aerial and terrestrial photos were processed through photogrammetry software to generate dense point clouds, meshed models, and textured models of the site. This case study examines the 3D workflow and results.Introduction related your research work Introduction related your research work Introduction related your research work Introduction related your research work Introduction related your research work.

2.2 Photogrammetry Workflow

The basic workflow utilized in RealityCapture to process the aerial and terrestrial photo datasets into a complete 3D model consisted of:

1. Photo Import - The 50 GB of photos were compressed by 50% to enable import within the demo memory limits.
2. Photo Alignment - The software automatically found common points between photos and matched them
3. Point Cloud Generation - Matched points were triangulated to generate a dense 3D point cloud.

4. Meshing - A polygonal mesh was constructed from the point cloud.
5. Texturing - Color data from source photos was mapped onto the mesh to texture it.
6. Component Merging – The separate aerial and terrestrial components were aligned and merged.
7. Optimization – The combined 3D model was decimated and refined for export.
8. Export - The model was exported to SketchUp for further modeling.

2.3 Photo Processing

Due to the large 50 GB combined dataset, the photos were compressed to approximately 3 MB per 12 MP image to reduce it to 25 GB total and enable import into the limited demo software. Even at this reduced resolution, the images retained adequate detail for modeling. Figure 3 shows samples of the aerial and terrestrial images. The software automatically detected common features between photos through SIFT (scale-invariant feature transform) feature matching (Lowe, 2004). Tens of thousands of matched points between photos enabled precise image alignment. The aligned images were then processed through bundle adjustment with additional parameters from camera metadata like focal length from EXIF data to triangulate matched points and generate a dense point cloud. The aerial and terrestrial photos produced separate aligned point clouds due to having completely different perspectives.

Fig -1: Sample input photos including aerial (left) and terrestrial (right)

The aerial and terrestrial photos produced separate aligned point clouds due to having completely different perspectives. The point clouds were converted into polygonal mesh models using default processing settings. The aerial point cloud generated a cleaner mesh since the points viewed the site from similar overhead perspectives. The terrestrial mesh contained noise from oblique viewpoints and needed more post-processing. Texture maps were created by projecting color data from the original photos onto each mesh to achieve photorealistic models. The aerial and terrestrial models were aligned but remained as separate components. To integrate the aerial and terrestrial data into a single comprehensive model, common points between the two components were manually matched. At least three common points are recommended to align components. The ground control points used for geo-referencing the aerial photos in the original survey were suitable merge markers. Though taken from different views, these stable points could be accurately identified in both model components as shown in Figure 2. With point matches set, the software merged the aerial and terrestrial components into an integrated model.

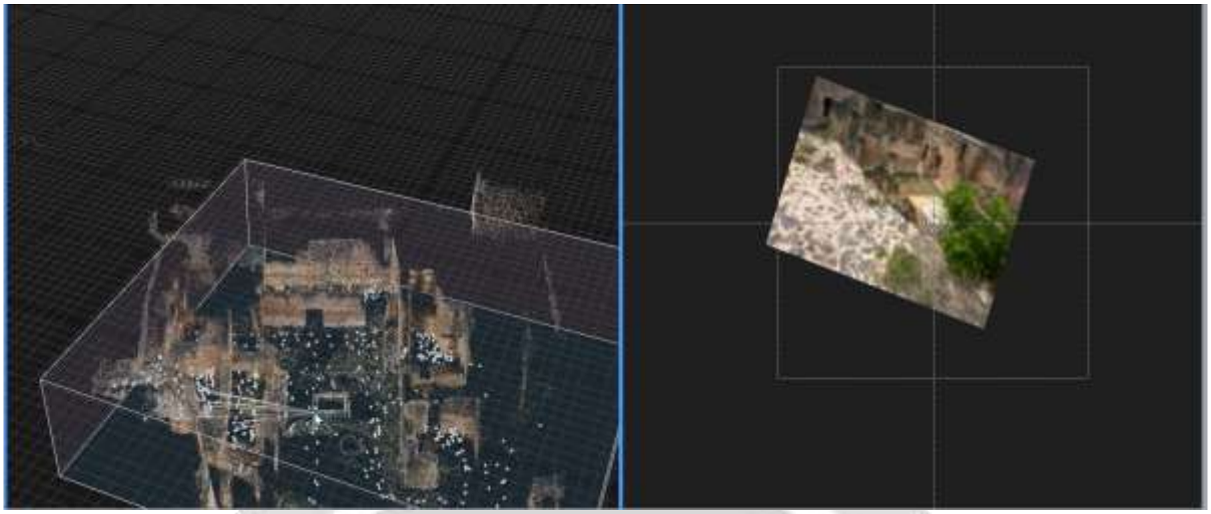

Fig -2: Screenshot of RealityCapture component merge using common ground control points between aerial (top) and terrestrial (bottom) models.

3. Model Optimization

The combined model was complex, containing noise, gaps, and redundant triangles. Model cleanup tools were utilized for optimization. Decimation reduced triangles for smoother geometry at lower file size. Hole filling patched missing areas by interpolating surfaces. The final optimized model contained clean geometry essential for export and interactive rendering. A textured view is shown in Figure 3.

Fig -3: Final textured 3D model of Kilwa Kisiwani fortress in RealityCapture following optimization and merging.

The optimized 3D model was exported from RealityCapture in SketchUp (.skp) format. SketchUp enables interactive navigation and scalable rendering for visualization. Texture maps were also exported to apply photorealistic textures within SketchUp. The model retained surveyed dimensions and could be measured or traced. Figure 4 shows the textured model in SketchUp, where it can also be annotated with callouts or converted to virtual reality formats. This photogrammetry modeling workflow of the Kilwa Kisiwani fortress, from processing 100 GB of photographs into a 3D model which can be interactively viewed, demonstrates the power of digital photogrammetry for archaeological reconstruction using commodity software and hardware. High accuracy models can be generated from site photography and UAVs at consumer equipment cost levels. The data can be revisited perpetually for in-depth spatial analysis impossible with traditional methods.

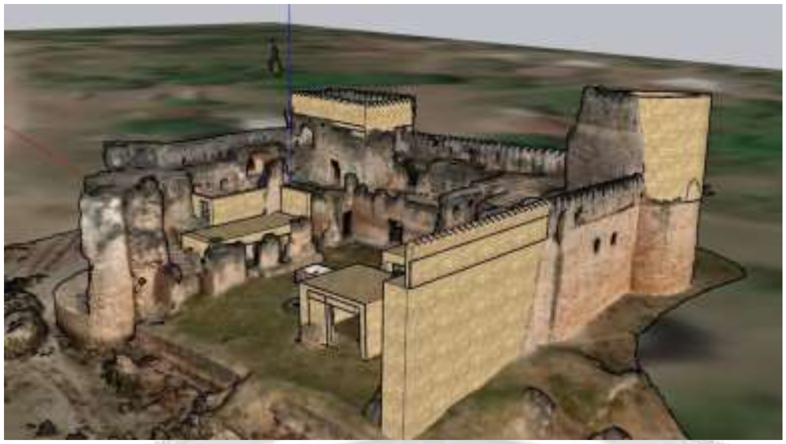

Fig -3: Kilwa Kisiwani fortress model rendered in SketchUp enables. interactive visualization and measurements.

3.1 Evaluation

The photogrammetry modeling workflow for this historic site successfully integrated aerial and terrestrial photographs into an accurate scaled 3D model. The RealityCapture software demonstrated automated processing of large datasets down to clean optimized models. The interactive model serves both visualization and analytic purposes. Measurements, structural details, deterioration, site changes over time, and virtual reconstructions can be studied in 3D space on a standard PC. The model provides a comprehensive digital record complementary to traditional site drawings and notes.

However, there were some limitations encountered. The original 100 GB of photos could not be fully processed within software memory limits. The 50% compression potentially lost fine details. Merging components required extensive manual alignment. Some architectural edges showed misalignment between aerial and terrestrial data likely due to geo-referencing discrepancies. The texturing blended images taken in variable lighting. Irregular UAV flight plans also led to uneven mesh resolution in areas.

Ultimately, the 3D model successfully preserved important spatial details, visible damage and deterioration, and the overall scope of the site. As aerial photogrammetry datasets grow larger, software continues improving to handle billions of points and pixels automatically. This project demonstrated a practical photogrammetry pipeline for accurate 3D archaeological reconstruction on consumer hardware. The model can now be leveraged for interactive education, digital preservation, and research.

4. CONCLUSIONS

This paper examined the use of photogrammetry, especially aerial photogrammetry from UAVs, to digitally reconstruct archaeological sites in 3D. Photogrammetry extracts precise 3D measurements from overlapping photographic images taken from different locations surrounding a subject. Triangulation of common points in photos enables generation of dense point clouds which are meshed and textured into photorealistic 3D models.

Aerial photogrammetry provides efficient large-scale topographic capture of excavations and structures. Integrated with terrestrial photogrammetry, comprehensive 3D site models with high geometric and texture resolution can be achieved. This is revolutionizing archaeological fieldwork, providing accurate digital records, metrics, and interactive 3D data. Spatial relationships, distances, volumes, profiles, cross-sections, and deterioration can be easily measured from the models. The Kilwa Kisiwani fortress case study successfully utilized aerial and terrestrial photographs to reconstruct the site in 3D through RealityCapture and SketchUp software. The 50 GB of photographs were processed into a textured mesh model with global scale retaining all survey measurements. This serves both visualization and analytic purposes. The workflow could be expanded upon with higher resolutions, optimized camera coverage, integrated LIDAR scans, multi-temporal data, VR applications, and computational analysis.

Photogrammetry provides a cost-effective means for archaeologists to preserve sites in 3D digital form for deeper study and engagement. The data enables interactive educational experiences, digital preservation, temporal change analyses, reconstruction simulations, predictive modeling, and quantitative measurement unattainable with traditional methods. 3D photogrammetry promises to be a pivotal technique as archaeology continues transitioning into a digital science in the 21st century.

5. REFERENCES

Almukhtar, A., Saeed, Z. O., Abanda, H., & Tah, J. H. M. (2021). Reality capture of buildings using 3D laser scanners. Multimodal Technologies and Interaction, 2(1), 12. https://doi.org/10.3390/mti2010012

Bisson-Larrivée, A., & LeMoine, J.-B. (2022). Photogrammetry and the impact of camera placement and angular intervals between images on model reconstruction. Digital Applications in Archaeology and Cultural Heritage, 26. https://doi.org/10.1016/j.daach.2022.e00343

Elkhrachy, I. (2021). Accuracy assessment of low-cost unmanned aerial vehicle (UAV) photogrammetry. Alexandria Engineering Journal, 61(2), 1363-1370. https://doi.org/10.1016/j.aej.2021.02.025

Lowe, D. G. (2004). Distinctive image features from scale-invariant keypoints. International journal of computer vision, 60(2), 91-110.

Mathys, A., Semal, P., Brecko, J., & Van den Spiegel, D. (2019). Improving 3D photogrammetry models through spectral imaging: Tooth enamel as a case study. PloS one, 14(8), e0220762. https://doi.org/10.1371/journal.pone.0220762

National Geographic Society. (n.d.). Archaeology. National Geographic. Retrieved December 5, 2022, from https://education.nationalgeographic.org/resource/archaeology

Photogrammetry. (n.d.). In ScienceDirect. Retrieved from https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/photogrammetry

Society for American Archaeology. (2015). What is archaeology? SAA. Retrieved December 5, 2022, from https://www.saa.org/about-archaeology/what-is-archaeology