A Semi-Automated Pipeline for Extracting Architectural Plans from 3D LiDAR Data of Ancient Heritage Sites

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Abstract

This paper presents a semi-automated pipeline for extracting architectural plans from terrestrial LiDAR point clouds of archaeological sites characterized by irregular geometries and significant surface degradation. The proposed workflow converts dense three-dimensional data into simplified two-dimensional representations by combining geometric alignment, expert-guided cross-section selection, feature detection using Intrinsic Shape Signatures (ISS), region-based segmentation, and polyline simplification. The method is specifically designed to handle rock-cut tomb environments, where erosion, noise, and non-planar surfaces complicate conventional Scan-to-Plan approaches. The pipeline is evaluated on six tombs from the Sheikh Said necropolis in Middle Egypt, covering a range of architectural configurations and preservation states. Results demonstrate that the method efficiently produces CAD-compatible outlines that capture the dominant structural geometry while significantly reducing manual drafting time. However, the accuracy of the generated plans depends on surface conditions, with degraded or ornamented areas introducing geometric artifacts that require expert refinement. The proposed approach provides a robust geometric baseline for archaeological documentation and highlights the potential of human-in-the-loop workflows for complex heritage environments.

1. Introduction

Automatically generating architectural plans from archaeological sites remains a challenging task, particularly in contexts where structures exhibit irregular geometries and significant degradation. Rock-cut monuments, in particular, present complex spatial configurations characterized by non-planar surfaces, collapsed features, erosion, and accumulated debris. These conditions complicate the extraction of reliable two-dimensional representations, such as floor plans and cross-sections, from three-dimensional survey data. The difficulty is further amplified when documenting vertical features, including narrow shafts and multi-level spatial arrangements, which are essential for understanding the architectural and functional organization of such sites.

The Sheikh Said necropolis in Middle Egypt exemplifies these challenges. Originally documented by Davies (Davies, 1901) through manual measurements and interpretative drawings, the site has undergone substantial natural and anthropogenic transformations over time. As a result, historical records no longer accurately reflect the current state of the tombs. While terrestrial laser scanning enables the acquisition of high-resolution and geometrically accurate point clouds, transforming these datasets into structured and interpretable architectural drawings remains a non-trivial task.

Existing Scan-to-Plan workflows often rely heavily on manual intervention, requiring experts to section point clouds and trace geometries in CAD environments. Although effective, these approaches are highly time-consuming, subjective, and difficult to scale across expansive archaeological sites. At the same time, fully automated methods struggle to handle the structural and environmental irregularities typical of heritage contexts. Traditional feature-extraction and segmentation algorithms are primarily developed for modern building environments characterized by vertical, plumb walls and well-defined planar surfaces. In contrast, rock-cut monuments feature intrinsic geometric noise caused by the subtractive nature of the architecture, natural rock morphology, and severe surface weathering. When automated algorithms attempt to extract boundaries from these uneven stone surfaces, they encounter severe limitations. Instead of processing a single, clean vertical plane, automated tracking tools are forced to navigate thousands of unorganized points reflecting surface roughness, protruding rock reliefs, or accumulated debris and rubble at the base of the walls. Because these multi-layered point distributions exist within the same structural zone, conventional mathematical simplification strategies fail to distinguish the macroscopic architectural boundary from localized micro-topography, making human-in-the-loop validation essential. This motivates the development of semi-automated approaches that combine computational efficiency with expert architectural knowledge.

In this paper, we propose a semi-automated pipeline for extracting architectural plans from LiDAR point clouds of rock-cut tombs. The method integrates geometric alignment, expert-guided cross-section selection, feature detection, segmentation, and contour simplification to produce CAD-compatible outlines. Rather than fully replacing manual drafting, the approach aims to generate a reliable geometric baseline that can be refined by domain experts, thereby reducing overall processing time while maintaining interpretability.

The remainder of this paper is structured as follows. Section 2 introduces the study area and dataset. Section 3 describes the proposed methodology in detail. Section 4 presents the results obtained on multiple tombs and evaluates the performance of the pipeline. Section 5 discusses the strengths and limitations of the approach in the context of archaeological documentation. Finally, Section 6 concludes the paper and outlines directions for future work.

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2. Study Area and Selected Assets

To validate the proposed algorithm in an authentic archaeological context, this study utilizes Terrestrial Laser Scanning (TLS) data acquired from the Sheikh Said necropolis in Middle Egypt. Dating back primarily to the Old Kingdom (Sixth Dynasty), the site consists of ancient tombs carved directly into the steep natural limestone cliffs along the eastern bank of the Nile (Davies, 1901). These structures were constructed as the final resting places for the provincial governors and high officials. As some of the earliest examples of fully developed rock-cut tombs, their architecture represents a transition from traditional mastabas to subterranean layouts. Because they are subtractive structures hewn from the living rock rather than built masonry, their spatial organization is inherently organic. The tomb interiors naturally lack straight lines, plumb vertical walls, or perfect right angles, presenting a continuous irregular morphology (Murphy et al., 2013). Furthermore, over the millennia, the limestone surfaces have suffered severe degradation due to natural weathering, geological fracturing, and later human interventions, including quarrying and reuse. Consequently, many of the original architectural features, such as wall reliefs and structural boundaries, are now obscured, resulting in highly noisy and complex point cloud data. Applying the new automated Scan-to-Plan technique to this pre-existing dataset provides an exceptionally demanding test, as the algorithm must navigate highly irregular rock-cut geometry, collapsed ceilings, deep burial shafts, and accumulated rubble (Grilli et al., 2017).

Within this research framework, a dataset of six tombs (Tombs 3, 18, 19, 24, 25, and 85) was selected to evaluate the algorithm. This selection was based on geomorphological factors and aims to cover a variety of architectural typologies found at the site. The tombs vary in general spatial complexity, ranging from relatively orthogonal, multi-chamber layouts featuring offering chapels and inner halls, to more organic, roughly excavated circular geometries. In addition, they were chosen to test how the algorithm handles highly uneven surfaces, as several of these tombs feature complex carved wall features, niches, false doors, and architectural reliefs (Davies, 1901). Despite these variations in shape and surface detail, all share the typical anomalies of rock-cut environments, including subterranean shafts leading to burial chambers that add a complex vertical dimension to the surveying process. To create a reliable baseline for comparison, 2D floor plans for all six tombs were drawn manually using traditional CAD tracing over sliced point clouds. This manual vectorization allows for a direct, layout-focused evaluation of the algorithm's performance across different levels of geometric complexity, providing a clear metric for assessing how accurately the automated pipeline captures the horizontal footprint and 2D boundaries of these intricate spaces.

3. Methodology

The proposed workflow processes massive, unstructured terrestrial LiDAR point clouds of archaeological tomb interiors to derive simplified, computationally efficient geometric representations of their structural profiles. The primary objective is to bridge the gap between high-resolution 3D data acquisition and traditional 2D Scan-to-Plan practices. By converting dense three-dimensional datasets into a compact set of vector contours, the methodology captures the dominant macro-geometry of the excavated chambers while remaining highly suitable for standard archaeological documentation and structural analysis. To achieve this, the method follows a rigorously structured semi-automated pipeline that deliberately integrates computational algorithms with domain-specific human expertise. Initially, the raw point cloud is globally aligned to a consistent geometric reference frame to establish a reliable vertical and horizontal datum. Following this spatial normalization, horizontal cross-sections are extracted at expert-defined elevations, ensuring that the slicing planes intersect the most architecturally informative zones rather than arbitrary heights. Within these extracted slices, salient geometric features are detected to filter out environmental noise and non-structural artifacts, allowing representative vector contours to be mathematically reconstructed from these keypoints. The final result is a simplified yet geometrically meaningful 2D description of the tomb profiles. This output acts as a foundational geometric scaffold that can be seamlessly exported into standard CAD environments, allowing heritage professionals to bypass the tedious initial drafting phase and focus directly on semantic detailing and architectural refinement.

3.1 Data Acquisition

For this study, the site was digitized using a *Leica BLK360* terrestrial laser scanner, chosen for its portability and ability to capture high-density point clouds in constrained underground environments. To ensure geometric accuracy, all scans were georeferenced using a control network established with a total station. Multiple individual scans were acquired to capture the tomb chambers, shafts, and external areas. These scans were subsequently registered and aligned into a unified coordinate system through a combination of target-based and cloud to cloud registration methods. The resulting dataset forms a consistent and spatially accurate 3D representation suitable for geometric extraction and 2D plan generation.

Before the main processing steps, point cloud pre-processing is performed in order to reduce the size of the raw LiDAR data. The original point clouds typically contain a very large number of points with significant local density variations. A voxel-based downsampling strategy is therefore applied, where the space is subdivided into regular cubic cells and a representative point is retained for each occupied voxel. This step decreases the computational burden of the subsequent processing stages while preserving the global geometry of the tomb structures.

3.2 Geometric Alignment

Archaeological tomb interiors typically contain a dominant planar surface, either at the ceiling or the floor. This characteristic allows the scene orientation to be estimated by detecting the plane that best represents this surface. A robust plane fitting procedure based on RANSAC (Chum and Matas, 2003) is used to estimate the parameters of this plane. The detected plane normal defines the orientation of the tomb structure, and the point cloud is rotated so that this normal aligns with the global vertical axis. As a result, the dominant architectural surface becomes approximately parallel to the horizontal plane.

3.3 Cross-Section Selection and Extraction

The extraction of cross-sections is a key component of the methodology because it determines how the three-dimensional geometry of the tomb is translated into interpretable two-dimensional profiles. Rather than applying a fully automated

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slicing strategy, the selection of cross-section heights is performed by an architect using CloudCompare. The architect visually inspects the point cloud and selects locations that best capture the geometric characteristics of the tomb chamber. This expert choice allows the sections to coincide with meaningful architectural transitions—such as floor levels, ceiling changes, niches, or structural discontinuities—that automatic slicing strategies may fail to identify.

These selected points define the target heights at which cross-sections are extracted. Each cross-section corresponds to a horizontal slice of the aligned point cloud, defined by retaining points within a small vertical tolerance around the selected height

$$|z - z_t| \leq \delta_z \tag{1}$$

where z_t is the selected cross-section height and δ_z defines the slice thickness. The resulting points are then projected onto the horizontal plane, producing a two-dimensional representation of the tomb profile at that elevation.

3.4 Geometric Feature Detection

The extracted cross-sections often contain a large number of points that include both meaningful structural features and noise originating from scanning artifacts, surface roughness, or irregular stone textures. To focus the analysis on the most informative geometric locations, salient points are detected using the Intrinsic Shape Signatures (ISS) keypoint detector (Zhong, 2009).

ISS identifies points with distinctive local geometric characteristics by analyzing the covariance structure of neighboring points. Locations where the eigenvalues of the local covariance matrix exhibit strong anisotropy correspond to geometric features such as edges, corners, or curvature changes. These points tend to represent the structural boundaries of the chamber and therefore provide an informative subset of the original cross-section data.

The use of ISS is particularly suited to archaeological tomb scans because the surfaces are rarely smooth or uniform. Carved walls, erosion, and acquisition noise generate irregular point distributions that can obscure structural boundaries. By selecting points based on their local geometric saliency, the ISS detector filters out large portions of uninformative points while retaining those that capture the essential shape of the chamber.

3.5 Region Segmentation and Adaptive Point Reduction

The detected keypoints form a sparse set of geometrically meaningful locations within each cross-section. However, due to the complex and cluttered nature of tomb interiors, these points often belong to several spatially distinct regions. In addition to the structural surfaces of the tomb, the point cloud may contain objects such as statues, excavation tools, fragments, or other elements present during the survey. These elements introduce additional clusters of points that do not correspond to the chamber boundaries.

To address this situation, the detected keypoints are grouped into spatial regions using a region-growing segmentation approach (Rabbani et al., 2006). Starting from randomly selected seed points, neighboring points within a fixed spatial radius are iteratively aggregated to form clusters. Repeating this process across several iterations allows the algorithm to identify coherent spatial regions while removing duplicate clusters. The largest and most consistent regions are then retained for further processing.

Once the regions have been identified, an adaptive point reduction procedure is applied within each region. Points are processed in random order, and when a point is selected as representative, neighboring points within a specified suppression radius are discarded. The suppression radius is adjusted according to the density of each region so that dense clusters are simplified more aggressively while sparse regions retain sufficient detail.

This combined strategy allows the method to isolate the dominant structural regions of the tomb while suppressing dense clusters caused by objects or local noise. The result is a small set of representative points that capture the geometry of each structural region in the cross-section.

3.6 Polyline Generation and Simplification

The final stage converts the representative points of each region into simplified geometric contours describing the tomb profile. The points are first ordered using a nearest-neighbor traversal to form an initial polyline approximation of the region boundary. Because archaeological scans frequently contain missing data or occluded areas, large gaps between consecutive points are detected and used to divide the polyline into separate segments. This prevents the algorithm from connecting distant points that do not belong to the same structural feature.

Each segment is then simplified using the Ramer–Douglas–Peucker algorithm (Pshikhachev and Karsakov, 2019), which removes intermediate vertices while preserving the dominant geometric shape of the polyline. The resulting contours provide a compact representation of the chamber profile that retains the principal geometric characteristics of the original data.

For each analyzed cross-section, the pipeline produces simplified polylines corresponding to the main structural regions of the tomb. These contours are exported to CAD environments, enabling efficient geometric measurements and integration into archaeological documentation workflows. In practice, these simplified contours serve as a geometric base layer upon which more detailed architectural plans can be traced. Archaeologists or architects can refine the automatically extracted outlines by adding additional features such as wall articulations, niches, doorways, pillars, and other architectural elements that may not be fully captured by the automated reconstruction, resulting in a more complete and interpretable plan of the tomb.

4. Results

To evaluate the proposed pipeline for extracting architectural plans from point clouds, the methodology is applied to six tombs selected to represent the main architectural features of the site. These examples include tombs with multiple chambers, niches and statues, burial shafts, and altars. The objective is to assess the robustness of the proposed approach when applied to complex heritage monuments with diverse architectural configurations. Figure 1 presents the outline drawings generated by our methodology alongside the manual drawings derived from the point cloud.

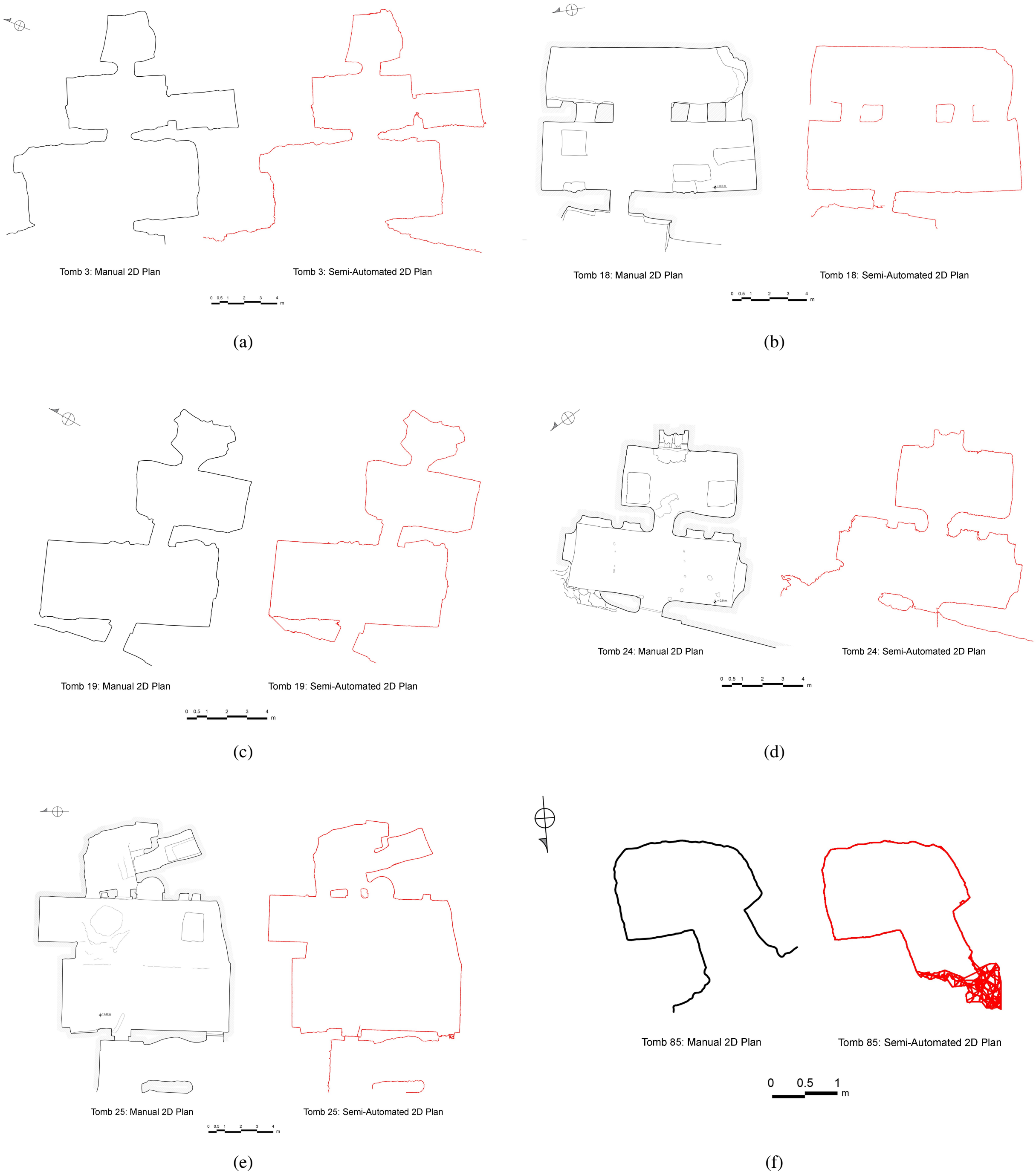

Figure 1. Comparison of automatically generated outlines and reference data across six tombs.

From a visual perspective, the automatically generated drawings capture in detail the geometry of the tombs. However, when zooming into certain sections, the lines are not always clearly delineated. As shown in Figure 2, segments that should ideally be represented by a single straight line are sometimes approximated by multiple short segments forming triangular or polygonal shapes. This behavior is attributed to several factors, including noise in the point cloud, registration errors, surface irregularities, and occlusions. Such artifacts may complicate the interpretation of the plans and may lead to misinterpretations by heritage experts.

To quantify the impact of these drawing errors, the percentage of segments that are not represented by a single straight line is estimated, together with the average area of the resulting polygons. These metrics provide an indication of the reliability of the automatically generated drawings in terms of usability and spatial accuracy. For simplicity, segments forming triangular polygons are identified and their respective areas are computed. The resulting metrics for each tomb are reported in Table 1.

Tomb	A	B	C	D	E	F
Avg. Length (cm)	3.8	4.1	3.5	4.3	3.9	4.3
% Triangles	12.5	14.2	10.8	11.2	13.4	14.9

Table 1. Quantitative evaluation of the drawing segments represented by triangular polygons instead of single straight lines.

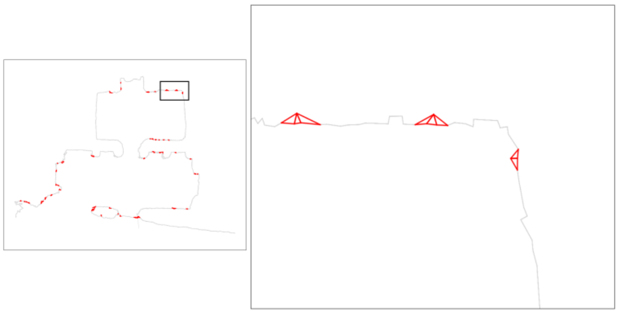

Figure 2. Example of the automatically generated outlines. Straight architectural edges that should be represented by single line segments are instead wrongly approximated by multiple short segments forming triangular polygons.

5. Discussion

To evaluate the automated pipeline, six different tombs of varying complexity were analyzed. The results demonstrate that the geometric accuracy of the algorithm is heavily dependent on the morphological clarity of the rock-cut surfaces. In tombs with relatively clean subtractive geometries, such as T3 and T19, the semi-automated vector output aligns almost perfectly with the manual reference plan. However, highly degraded or heavily ornamented architecture introduces significant challenges (Grilli et al., 2017). For instance, in T24, the sculpted reliefs and idols on the walls prevent the algorithm from identifying a single planar face. The algorithm interprets these depth variations as structural geometry, resulting in a vector output of small triangular polygons. Because these multi-layered point distributions exist within the same structural zone, it fails to distinguish the macroscopic architectural boundary from localized microtopography. Consequently, the automated workflow struggles to fit single straight polylines, instead generating dense arrays of short, interconnected segments that form artificial triangular or polygonal artifacts. In such cases, the software mistake localized surface noise and debris for structural lines, whereas the architect intuitively ignores the superficial ornamentation and accumulated rubble to trace the true structural wall.

From an architectural standpoint, the pipeline provides a rapid geometric baseline, but requires expert intervention for the final plan. One factor is the Z-height of the slicing plane. As seen in T85, if the horizontal slice intersects with floor rubble, the algorithm extracts this as "noise." Removing these artifacts requires only minor manual post-processing and does not compromise the main outline. More importantly, the algorithm extracts a strict 2D planar outline. As illustrated in T18, T24, and T25, the automated outline captures the external boundary perfectly but misses critical spatial depths. An architect manually projects floor variations, steps, and deep burial shafts into the plan. Therefore, the algorithm acts as a foundational tool that eliminates the tedious initial drafting of irregular rock walls, allowing the expert to focus on semantic detailing.

Traditionally, extracting plans involves sectioning the point cloud in software such as CloudCompare and manually tracing it in AutoCAD (Murphy et al., 2013). This fully manual approach typically requires 60 to 90 minutes for a single plan, depending on its complexity. In stark contrast, the proposed automated script generates CAD-compatible vectors in just about 30 seconds per Z-section. Even when factoring in the necessary pre-processing steps and the subsequent manual architectural refinements, this rapid geometric baseline significantly accelerates the workflow. Overall, the total drafting time is reduced to approximately a quarter of what a strictly manual approach demands. Furthermore, the raw automatic outputs are exceptionally valuable for non-CAD experts. For field archaeologists and surveyors, the algorithm rapidly provides georeferenced, to-scale outlines. This enables the immediate mapping of the necropolis layout directly on-site, aiding in excavation planning without waiting for completed architectural drawings.

6. Conclusion

This paper presented a semi-automated pipeline for generating architectural plans from massive terrestrial LiDAR point clouds of complex archaeological sites. The proposed approach systematically combines robust geometric alignment, Intrinsic Shape Signatures (ISS) feature detection, region-growing segmentation, and polyline simplification to extract meaningful two-dimensional vector representations from unstructured three- dimensional data. Applied to multiple rock-cut tombs at the Sheikh Said necropolis, the method demonstrates its ability to reliably produce CAD-compatible outlines. These simplified contours successfully capture the dominant structural geometry of the ancient chambers, bridging the gap between raw point cloud acquisition and functional heritage documentation while significantly reducing the tedious manual drafting effort traditionally required.

The evaluation results highlight the overall effectiveness of the pipeline as a rapid geometric baseline generation tool, performing exceptionally well in relatively clean and distinct architectural contexts. At the same time, the quantitative and qualitative assessments reveal specific algorithmic limitations when handling highly degraded, uneven, or heavily ornamented rock surfaces. In such areas, inherent geometric noise, surface erosion, and accumulated debris cause the mathematical simplification algorithms to misinterpret micro-topography as macroscopic structural boundaries, leading to the generation of localized approximation artifacts, such as triangular polygonal segments. These findings confirm that fully automated Scan-to-Plan solutions are not yet viable for highly irregular heritage environments. Instead, expert intervention remains strictly necessary to filter out superficial anomalies and refine the final architectural plans, ultimately supporting a highly efficient human-in-the-loop approach to archaeological documentation.

As the proposed pipeline is currently in its initial stage of development, future work will focus on systematically expanding its computational capabilities and geometric outputs. A primary goal is to adapt and scale the algorithm to automatically extract vertical cross-sections alongside the horizontal plans, which are absolutely essential for a comprehensive structural and spatial documentation of subtractive monuments. Furthermore, for both horizontal plans and vertical sections, future software iterations should project a localized subset of the 3D point cloud data directly onto the 2D slicing planes. This point-projection feature would create a dense visual underlay, allowing architects and heritage experts to quickly and intuitively trace polylines over the visible spatial depths. Implementing this feature would significantly accelerate the manual addition of critical non-planar elements—such as deep burial shafts, sunken altars, stepped descents, and overhead ceiling projections—paving the way for more holistic and time-efficient 3D-to-2D archaeological mapping.

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