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When Reality Meets Practice: Challenges and Pitfalls in 3D Digitization Using Structured Light Scanning and Photogrammetry in Cultural Heritage

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Abstract

Three-dimensional (3D) digitization has become a central methodological pillar in cultural heritage documentation, conservation support, and dissemination. Despite the maturity of image-based photogrammetry and active sensing technologies, real-world digitization campaigns frequently diverge from idealized workflows due to constraints related to object accessibility, surface properties, lighting conditions, and operational feasibility. As a result, practitioners are often required to adapt acquisition and processing strategies dynamically, balancing geometric fidelity, visual quality, and practical limitations. This study presents a practice-oriented analysis of applied digitization workflows conducted in controlled indoor and museum environments, focusing on fragile and optically challenging cultural and paleontological objects. Structured light scanning, DSLR-based photogrammetry, and hybrid approaches were systematically explored. While structured light scanning offered high nominal resolution, its performance proved sensitive to material properties and surface behavior, leading to incomplete or unstable reconstructions in several cases. Photogrammetric workflows, when supported by controlled acquisition setups, yielded robust and visually coherent results for the majority of objects. For cases where conventional photogrammetry underperformed, alternative AI-assisted image-based reconstruction pipelines were evaluated as complementary solutions. Rather than emphasizing only successful outcomes, the paper documents recurring failure modes, decision-making trade-offs, and breakdown points across acquisition, alignment, meshing, and texturing stages. Empirical observations are synthesized into qualitative comparisons and decision-support tables, highlighting the conditions under which specific digitization strategies succeed or fail. The findings underscore that hybrid workflows, while theoretically advantageous, can amplify integration complexity and error propagation if not carefully constrained. By foregrounding practical constraints and adaptive methodological choices, this work contributes a transparent, experience-driven perspective on cultural heritage digitization, supporting more resilient planning and informed decision-making in future documentation and conservation projects.

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1. Introduction

Three-dimensional (3D) digitization has become a core methodological component of cultural heritage documentation, conservation support, and dissemination. Image-based reconstruction techniques (photogrammetry/SfM-MVS) and active range sensing methods (e.g., terrestrial laser scanning and structured light scanning) are widely adopted to generate digital surrogates and, increasingly, operational digital twins that support documentation, interpretation, and lifecycle management of heritage assets [1,2]. Comparative studies consistently demonstrate that these techniques involve distinct trade-offs in geometric fidelity, radiometric quality, acquisition effort, and operational constraints, which has motivated the adoption of hybrid digitization approaches in practice [3,4].

Despite the maturity of these technologies, real-world digitization campaigns frequently diverge from the assumptions underlying "ideal" acquisition and processing pipelines. Photogrammetric reconstruction relies on stable illumination, sufficient viewpoint overlap, and robust feature detection; consequently, low-texture surfaces, repetitive patterns, specular highlights, shadows, and restricted viewpoints can destabilize camera alignment and degrade dense surface reconstruction [5,6]. Even when geometric reconstruction is successful, texture quality remains highly sensitive to radiometric inconsistencies across image sets—a condition that is common in museum, storage, and laboratory environments where lighting cannot be fully controlled. Structure-from-motion photogrammetry has been increasingly adopted in paleontological contexts, supporting documentation, research, preservation, and educational dissemination under field and museum constraints [5,7].

Structured light scanning (SLS), often selected for small- to medium-scale artifacts due to its potential for high-resolution surface capture, exhibits a different but equally restrictive set of dependencies. Pattern projection and decoding typically assume near-Lambertian surface behavior; reflective, glossy, dark, translucent, or heterogeneous materials can lead to missing data, noisy depth measurements, or systematic distortions that are difficult to correct in post-processing [8,9]. In cultural heritage contexts, conservation ethics and object-handling constraints may further limit mitigation strategies (e.g., surface treatments), while mounting systems, supports, and proximity to surrounding structures can restrict access and necessitate fragmented acquisition with increased registration effort.

To address the individual limitations of each modality, the integration of heterogeneous datasets is frequently proposed, particularly combining laser scanning and photogrammetry [10]. However, such hybrid workflows introduce additional challenges, including cross-sensor registration, scale consistency, uneven sampling density, and the propagation of local acquisition errors into the merged geometry and texture [11]. As a result, hybrid approaches may not simply "solve" modality-specific weaknesses but instead fail in different—and sometimes less predictable—ways, particularly when acquisition sessions are separated in time or conducted under varying radiometric conditions.

Building on our previously validated digitization and digital twin methodologies in museum and cultural space settings [12,13], this paper focuses explicitly on the gap between theoretical digitization pipelines and applied practice. We systematically document recurring failure modes and decision-making pitfalls encountered across acquisition, alignment, meshing, texturing, and optimization stages. Rather than presenting only successful case outcomes, we emphasize practical breakdown points and empirically grounded mitigation

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strategies, aiming to contribute a transparent, practice-oriented perspective that supports more resilient and realistic digitization planning in cultural heritage contexts.

The remainder of this paper is structured as follows. Section 2 reviews the relevant background and related work on photogrammetry, structured light scanning, laser scanning, and hybrid digitization approaches in cultural heritage. Section 3 presents the materials, case-study context, and applied digitization methodology, detailing acquisition setups, alignment strategies, and integration workflows. Section 4 discusses the main challenges and recurring pitfalls observed during applied 3D digitization, focusing on acquisition, registration, texturing, and integration under real-world constraints. Section 5 synthesizes these observations into a practice-oriented mitigation framework and decision-support perspective. Section 6 reports the empirical outcomes and qualitative results derived from the applied workflows. Finally, Sections 7 and 8 discuss the limitations of the study and conclude the paper, outlining directions for future research.

2. Background and Related Work

Cultural heritage digitization has matured into a multi-technology ecosystem, where methodological choices are shaped by object typology, environment, accessibility, and target use (documentation, analysis, dissemination, or digital twins). Early cultural heritage-oriented overviews already highlighted that no single acquisition method is universally optimal and that practical constraints (occlusions, materiality, scale, and logistics) dominate real deployments [1]. More recent comparative studies reaffirm that photogrammetry, terrestrial laser scanning, and structured light scanning provide different accuracy–cost–time trade-offs and should be selected against explicit quality requirements and constraints [3,4].

From a survey methodology perspective, geometric scaling, control measurement strategies, and cross-validation between sensing modalities constitute fundamental components of rigorous object documentation practice. Established photogrammetric and laser-scanning standards emphasize the role of calibrated scale bars, control networks, and accuracy assessment in ensuring dimensional reliability and reproducibility [14–16]. In archaeological object recording, these principles are particularly relevant when acquisition conditions are constrained and multi-session workflows are required.

Photogrammetry and SfM-MVS pipelines are attractive due to low equipment cost, portability, and simultaneous capture of geometry and appearance. Nonetheless, the reliability of these pipelines is tightly coupled to image quality and the stability of feature matching and bundle adjustment. Comparative studies between survey-grade photogrammetry and smartphone-based applications further demonstrate that increased accessibility often introduces accuracy and stability trade-offs [17]. Similarly, the combination of smartphone LiDAR sensing and photogrammetry has been explored for challenging heritage sites where access and lighting constraints limit conventional acquisition strategies [18]. App-based SfM solutions such as Polycam have also been comparatively evaluated for architectural structures and decorative motifs, revealing substantial variability in output quality depending on object scale, surface detail, and capture strategy [19].

SfM-based reconstructions can degrade under weak texture, specular highlights, motion blur, exposure shifts, or restricted viewpoints—conditions common in museum digitization, where objects may not be moved, lighting cannot be redesigned, and access is partial [5,6]. Dense matching quality can further vary substantially across materials and scales, which impacts surface noise, completeness, and the amount of manual cleanup required [11]. These technical instabilities and quality risks are well documented in recent analyses focusing on the challenges inherent in cultural heritage 3D acquisition workflows [20].

Structured light scanning is often positioned in the literature as a high-resolution alternative for artifacts, but its performance depends on projector–camera calibration, ambient illumination control, and favorable surface reflectance. Tutorials and surveys on structured-light measurement emphasize that reflectivity and translucency can break the correspondence between projected pattern and imaged response, producing holes and depth artifacts [8]. In CH, this limitation is not merely technical: conservation practice may restrict physical interventions (e.g., coatings), while exhibition or storage setups (supports, cradles, mounts) can reduce line-of-sight and force multi-pass scanning with complex registration [9].

Because these modalities fail under different conditions, hybrid digitization is widely adopted: laser scanning, or SLS, is used for robust geometry capture, while photogrammetry contributes radiometric detail and fills gaps when feasible. Reviews of multi-source cultural heritage documentation stress that the integration step is often the true bottleneck, requiring careful control of scale, overlap, and error propagation [2]. Cross-sensor fusion can introduce systematic misregistration when datasets differ in sampling density, noise characteristics, or coverage; these effects become visible as seams, local surface distortions, and texture projection inconsistencies, especially on objects digitized across separate sessions.

Despite these methodological frameworks, relatively limited attention has been paid to how these approaches perform when applied under constrained museum conditions and material-specific limitations. Within this context, our previous work has provided end-to-end digitization methodologies for museum exhibits and cultural spaces, explicitly combining photogrammetry with structural laser scanning to produce digital twins and dissemination-ready assets [12,13,21]. The present study extends this line by focusing on the "non-ideal" layer of digitization practice: where and why pipelines break, how constraints drive suboptimal decisions, and which mitigation tactics are effective under realistic cultural heritage conditions. From a decision-making perspective, this further reinforces the importance of documenting constraints and trade-offs alongside technical outcomes [22].

3. Materials and Methods

This study adopts a practice-oriented methodological approach grounded in real-world cultural heritage digitization campaigns conducted in museums and controlled indoor environments. Rather than proposing or validating an idealized acquisition pipeline, the methodology reflects operational decisions made under practical constraints, including limited object accessibility, non-ideal lighting conditions, heterogeneous surface properties, conservation restrictions, and available equipment.

The adopted workflow combines image-based reconstruction (photogrammetry) with range-based acquisition trials using a portable structured-light/laser scanning system (Einscan Pro HD). These acquisition modalities were complemented by dedicated post-processing, alignment, texture-mapping, and optimization stages. Method selection and adaptation were driven not by theoretical optimality but by observed performance under applied conditions, with particular emphasis on robustness, repeatability, and suitability for paleontological analysis and dissemination.

3.1. Case Study Context and Object Characteristics

The examined digitization cases originate from applied campaigns conducted in the Museum of Paleontology of the National and Kapodistrian University of Athens. The objects comprise medium-scale paleontological specimens, including skulls, shells,

vertebrae, and horn fragments, characterized by irregular geometry, fine morphological detail, and heterogeneous surface textures.

The selected specimens were not chosen to represent "ideal" scanning targets but rather to reflect the typical material, mounting, and conservation conditions encountered in mid-scale museum paleontological collections. These objects are part of the permanent exhibition and research collection of the museum and were selected in consultation with curatorial staff based on documentation priority and accessibility constraints, rather than on optical or geometric suitability for digitization.

Consequently, the observed methodological challenges should not be interpreted as atypical failures but as representative of realistic digitization scenarios in heritage institutions where object repositioning, environmental redesign, or surface treatment are not permissible.

These artifacts present a combination of material and geometric challenges that are representative of fragile organic and semi-organic heritage objects. Surface properties range from matte to semi-glossy and locally translucent, while morphological features include undercuts, cavities, thin edges, and high-frequency surface detail. In several cases, specimens were mounted on supports or positioned in proximity to surrounding structures, limiting physical access and preventing uniform 360-degree acquisition.

From a domain perspective, the primary requirements articulated by paleontological experts emphasized high-fidelity visual documentation, including accurate color representation and fine surface detail, to support morphological observation, comparison, and interpretive analysis. Metric precision at the level required for engineering or manufacturing applications was not the dominant objective; instead, visual reliability and morphological readability were prioritized.

The emphasis on visual fidelity and morphological readability aligns with prior paleontological applications of SfM photogrammetry, where accessibility, documentation, and educational reuse are key drivers rather than strict metrological accuracy [7]. These characteristics directly informed methodological decisions throughout the workflow. In particular, they motivated the evaluation of both photogrammetry and portable range-based scanning as potential acquisition strategies, as well as the subsequent prioritization of image-based reconstruction for the majority of specimens when range-based data proved insufficiently robust under the observed surface and access constraints, as shown in Figure 1 below.



Figure 1. Representative paleontological specimens digitized in this study, illustrating the diversity in geometry, scale, and surface texture that influenced acquisition and processing strategies.

Before detailing the individual acquisition and processing stages, it is important to clarify the overall decision logic that structured the applied digitization workflow. Rather than following a single predefined pipeline, the methodology evolved through a sequence of exploratory, evaluative, and corrective steps driven by the material properties of the objects, acquisition constraints, and observed reconstruction stability.

Figure 2 summarizes the practice-driven pipeline adopted in this study. Structured light scanning was initially selected due to its theoretical suitability for small- to medium-scale artifacts; however, systematic surface-related failures led to the early termination of this branch. Photogrammetry under controlled indoor conditions subsequently became the primary acquisition strategy and yielded stable results for the majority of objects when processed in Agisoft Metashape [23]. In a limited number of cases where dense reconstruction or texture fidelity proved insufficient, the workflow reverted to an AI-assisted photogrammetry solution, producing usable geometry through an alternative reconstruction pathway. Parallel experiments combining laser-derived and image-based geometry were also conducted but were ultimately discarded due to registration instability and cumulative geometric error.

This decision framework contextualizes the methodological choices discussed in the following subsections and highlights the gap between nominally "recommended" techniques and their effective performance under applied cultural heritage constraints.

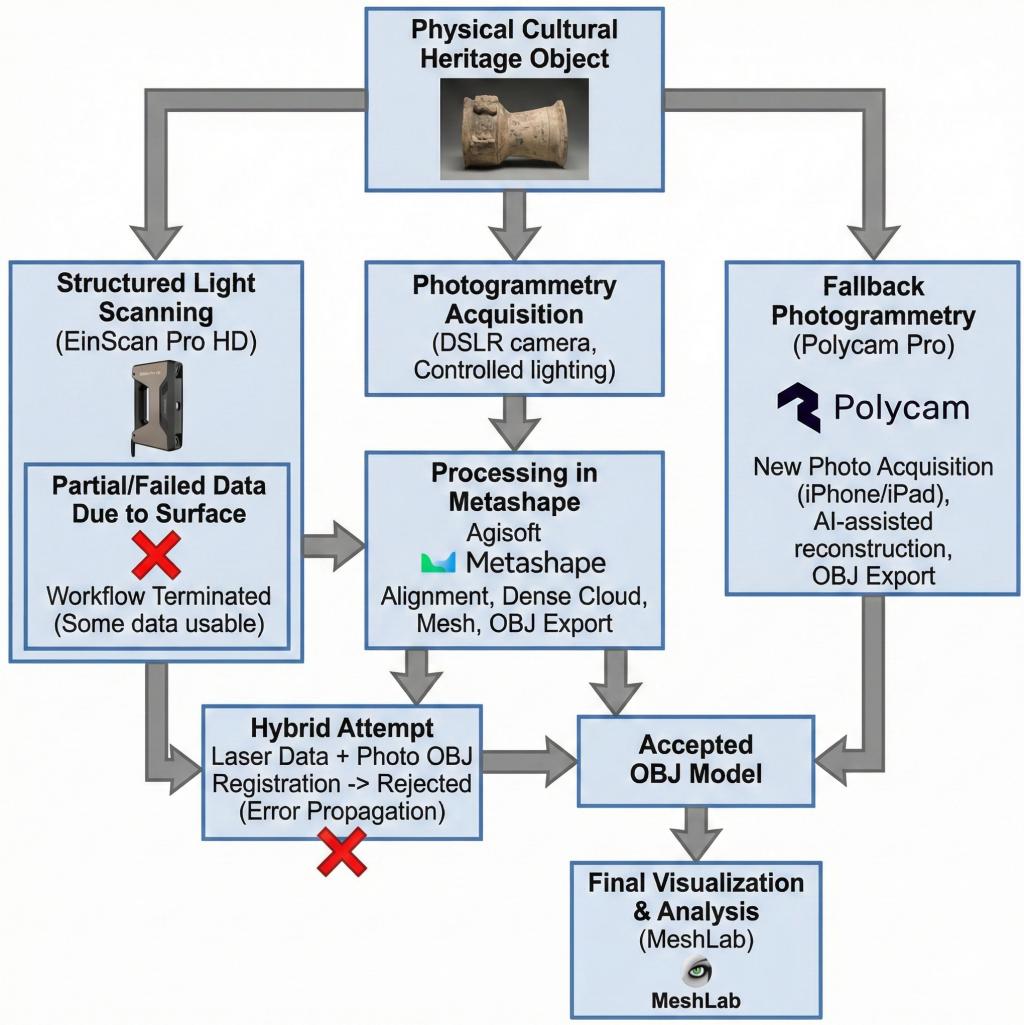


Figure 2. Practice driven digitization pipeline illustrating the evaluated acquisition paths, including structured light scanning, photogrammetry, AI-assisted reconstruction, and experimental hybrid integration.

It should be noted that this study deliberately prioritizes constraint-driven scenarios over idealized acquisition conditions. While a "near-ideal" specimen under fully controlled illumination and unrestricted access could produce higher reconstruction stability, such conditions are rarely representative of museum practice. The objective

was therefore not to benchmark optimal performance but to document behavior under realistic institutional constraints.

3.2. Structured Light Scanning Setup—Practice and Observations

A portable structured-light/laser scanning system (Einscan Pro HD) was initially evaluated for digitizing a subset of the paleontological specimens. In principle, such systems can deliver dense geometric sampling and high local surface detail in small- to medium-scale artifacts under controlled conditions. In our applied setting, however, performance was strongly bounded by the optical and geometric characteristics of the objects, as well as by access constraints typical of museum and storage environments.

The examined specimens (e.g., skull fragments, shells, horn elements) exhibited complex morphology with deep concavities, thin edges, undercuts, and high-frequency micro-relief. At the same time, their surfaces frequently presented heterogeneous optical behavior, including locally glossy or semi-reflective regions, subtle translucency, and mixed matte–specular response. Under these conditions, the scanner output repeatedly exhibited incomplete coverage and localized degradation: missing patches were common in recesses and along thin anatomical features, while certain surface regions showed elevated noise or irregular depth artifacts. These effects were not isolated but spatially systematic, indicating sensitivity to materiality and viewing geometry rather than sporadic acquisition errors.

Operational constraints further amplified these limitations. Several objects were mounted on supports or placed in proximity to adjacent structures, restricting line-of-sight and preventing continuous, uniform coverage. As a result, scanning had to be conducted in fragmented passes. Although standard registration procedures (including ICP-based alignment) were applied to merge partial scans, robust fusion was not consistently achievable when overlap was limited or when the individual passes differed in noise characteristics and sampling density. In such cases, the merged meshes tended to show small but perceptible seams and local distortions unless extensive manual correction was introduced, which conflicted with the throughput requirements of the campaign (Figure 3).

The structured-light system employed in this study (EinScan Pro HD) represents a widely accessible mid-range portable scanner frequently used in applied cultural heritage practice. High-end metrology-grade systems (e.g., Artec Spider II or Creaform GO!SCAN 3D) may provide improved stability under certain optical conditions; however, their cost, calibration requirements, and operational complexity often exceed the logistical framework of medium-scale museum campaigns. The focus of this study was therefore not on inter-device benchmarking but on workflow behavior under commonly accessible equipment conditions.

Overall, the structured-light/laser scanning trials indicated that, for the specific class of optically and geometrically challenging specimens examined here, range-based acquisition could not be relied upon as a primary, repeatable digitization method. Consequently, its role in the workflow was re-scoped to a selective, complementary modality used only in optically favorable regions or for coarse geometric support when image-based reconstruction proved incomplete. This practice-driven outcome aligns with prior work highlighting that structured-light performance is highly dependent on near-Lambertian surface response, controlled illumination, and favorable access conditions, which are not always attainable in cultural heritage digitization scenarios [8,9,11].

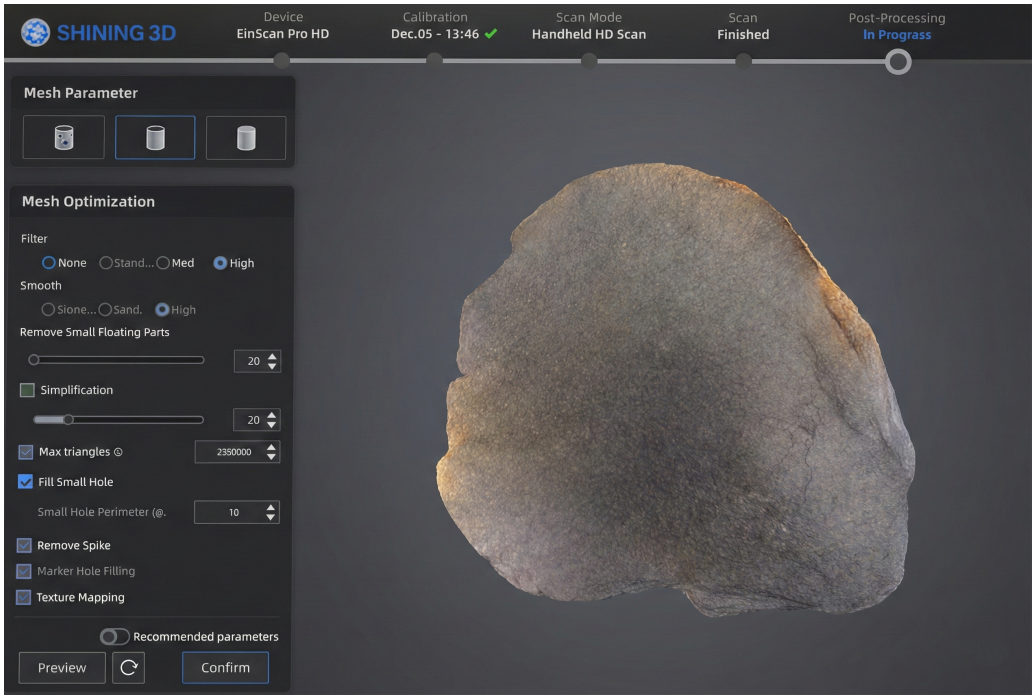


Figure 3. Representative output from structured-light scanning (EinScan Pro HD) applied to paleontological specimens. Despite stable calibration, the reconstructed mesh exhibits spatially consistent noise, missing regions, and surface instability in areas characterized by heterogeneous reflectance and concave morphology.

3.3. Photogrammetric Image Acquisition

Following the practical limitations observed during structured-light/laser scanning, photogrammetry was adopted as the primary acquisition method for the majority of the examined specimens. This decision was driven by the need to capture diagnostically relevant surface appearance and fine morphological detail, which are critical for paleontological interpretation and were insufficiently represented in the range-based scans.

Image acquisition was conducted in a controlled indoor environment using a full-frame DSLR camera equipped with a 50 mm fixed focal length lens. No dedicated macro lens was employed; instead, object-to-camera distance was adjusted to maintain sufficient depth of field while preserving image sharpness. The choice of a fixed focal length lens minimized geometric distortion and ensured stable intrinsic calibration across acquisition sessions.

To mitigate hard shadows and specular highlights, several diffuse light sources were positioned around the setup. Although complete radiometric control was not achievable, exposure settings and white balance were fixed throughout each acquisition session to reduce inter-image variability. Despite these precautions, residual illumination differences were observed, particularly on darker or semi-reflective surfaces, reflecting typical constraints in museum and storage-room digitization contexts.

Due to physical access limitations and conservation restrictions, full 360-degree coverage in a single session was often not feasible. As a result, multiple photographic datasets were acquired for different object orientations (e.g., upper and lower surfaces). Each dataset was processed independently before being aligned into a common reference frame during later stages. This multi-session strategy introduced additional alignment complexity but was necessary to ensure sufficient coverage of occluded regions.

Image sets were processed using standard SfM-MVS pipelines to generate sparse and dense point clouds, followed by mesh reconstruction and texture generation. In practice, the quality of the photogrammetric reconstructions varied across specimens and surface

regions. Objects with rich visual texture and stable illumination yielded dense, coherent geometry and high-quality texture maps, whereas areas characterized by weak texture, repetitive patterns, or residual specular highlights exhibited increased noise, local surface degradation, or incomplete reconstruction, as shown in Figure 4 below.



Figure 4. Lightning setup during photogrammetry process.

For selected specimens where traditional photogrammetric processing produced unstable or incomplete results, alternative image-based reconstruction workflows were explored as a complementary solution. These workflows employ advanced image processing and machine-learning-based optimization to enhance depth estimation and surface continuity. While such approaches demonstrated improved robustness in challenging cases, they were treated as supportive rather than primary methods within the overall digitization strategy.

Unlike traditional SfM pipelines, the AI-assisted reconstruction workflow employs depth estimation and surface inference mechanisms trained on large-scale image datasets. While proprietary implementation details are not fully disclosed by the platform, the underlying approach integrates multi-view feature matching with learned priors for depth continuity and surface regularization. In practice, this resulted in improved reconstruction stability in weak-texture regions and partially occluded geometries, although at the cost of reduced transparency in parameter control and reproducibility compared to conventional SfM-MVS pipelines.

Overall, photogrammetry proved to be the most effective acquisition modality for the examined paleontological objects, particularly in terms of radiometric fidelity and visual interpretability. The observed limitations—stemming from illumination variability, access constraints, and surface optical properties—were addressed through careful acquisition planning and subsequent processing rather than by reliance on a single automated solution.

3.4. Photogrammetric Processing and Mesh Generation

Photogrammetric processing was conducted using a structure-from-motion (SfM) and multi-view stereo (MVS) pipeline, with Agisoft Metashape employed as the primary reconstruction environment. The objective of this stage was to generate dense point clouds and polygonal meshes suitable for subsequent integration and texture mapping while critically evaluating the robustness of conventional photogrammetry under applied museum and laboratory constraints.

Image alignment was performed using feature-based camera matching and bundle adjustment. Despite careful acquisition planning, alignment stability varied across datasets, particularly for specimens exhibiting weak surface texture, repetitive morphological patterns, or subtle chromatic variation. In several cases, tie point distribution was spatially uneven, with localized clusters and redundant correspondences leading to unstable camera geometry. To mitigate these effects, iterative tie point filtering was applied using reprojection error and reconstruction uncertainty thresholds. However, aggressive filtering frequently resulted in a substantial reduction of valid tie points, highlighting the sensitivity of SfM pipelines to non-ideal surface and illumination conditions.

Dense point cloud generation was subsequently performed using depth-map-based MVS reconstruction. While satisfactory surface continuity was achieved for several specimens, others exhibited fragmented or noisy reconstructions, particularly in concave regions, thin anatomical features, and areas affected by subtle specular response. These deficiencies were not random but spatially consistent, indicating systematic acquisition and matching limitations rather than isolated processing errors. Increasing reconstruction density parameters did not consistently improve results and, in some cases, amplified noise without recovering missing geometry.

Polygonal mesh generation from dense point clouds produced visually coherent surfaces for a subset of objects; however, topological artifacts, surface roughness, and incomplete regions were recurrent. These issues necessitated additional post-processing using MeshLab, which was employed exclusively for mesh-level operations rather than reconstruction. MeshLab was used for background geometry removal, isolated component deletion, hole filling, and controlled smoothing. Importantly, these operations were applied conservatively to avoid introducing artificial geometry or obscuring diagnostically relevant surface detail [24].

A critical limitation observed during this stage was the reliance of the reconstructed meshes on vertex color information rather than stable, high-resolution texture maps. In cases where dense reconstruction quality was compromised, subsequent texture projection amplified geometric inaccuracies, leading to a blurred or distorted appearance. This reinforced the dependency between geometric reliability and radiometric fidelity within traditional photogrammetric pipelines.

Overall, the photogrammetric processing stage demonstrated that, under applied cultural heritage constraints, conventional SfM-MVS workflows can yield acceptable results for certain object classes but remain fragile for specimens characterized by complex morphology, subtle texture, or optical ambiguity. These observations informed subsequent methodological decisions, particularly regarding dataset integration strategies and the selection of appearance-driven reconstruction approaches, which are discussed in the following sections.

3.5. AI-Assisted Image-Based Reconstruction Trials (Contingency Path)

In a limited subset of specimens where conventional SfM-MVS processing in Metashape became unstable (e.g., weak texture, partial occlusion, or repetitive patterns leading to sparse tie-point geometry and fragmented dense clouds), we evaluated an AI-

assisted image-based reconstruction pipeline as a contingency pathway. The platform used in our trials provides only partial methodological disclosure; therefore, we do not claim algorithmic novelty nor full reproducibility at the level of internal model parameters. However, we report the aspects that are controllable and observable in practice: (i) identical input image sets were used as in the SfM pipeline (same acquisition rings and exposure discipline), (ii) reconstructions were generated using the platform's image-based 3D reconstruction mode, (iii) the produced outputs (mesh and texture) were exported in standard formats for inspection and downstream processing, and (iv) results were compared against the SfM-MVS baseline using our qualitative criteria (Section 3.9) and the semi-quantitative indicators recorded per dataset (aligned images, reprojection error after filtering, dense cloud completion, and mesh statistics).

Across the evaluated datasets, image alignment rates ranged between 82% and 96% of the total input images, depending on object morphology and surface texture. After tie-point filtering, average reprojection error values varied between 0.38 and 0.71 pixels, with higher values consistently associated with weak-texture or partially occluded regions. Dense point clouds ranged from 6.2 to 18.5 million points per specimen, with localized depth-map incompleteness observed primarily in concave or optically unstable areas.

Following mesh generation, initial polygon counts varied between 2.1 and 7.8 million faces, while curvature-aware decimation reduced dissemination-ready models to 350k–950k faces without perceptible loss of diagnostically relevant morphology. Cross-modality ICP alignment revealed no systematic global scaling bias, with localized deviations concentrated in thin morphological features and deep concavities rather than uniformly distributed across surfaces.

Empirically, the AI-assisted pathway improved surface continuity in weak-texture regions and reduced "catastrophic" failure cases (i.e., non-reconstructable geometry) in some specimens, but it also reduced transparency in parameter control and made systematic error diagnosis more difficult compared to SfM-MVS. For these reasons, we treat AI-assisted reconstruction strictly as a complementary, last-resort option within a constraint-aware digitization strategy.

3.6. Data Alignment and Geometry Integration

The integration of heterogeneous geometric datasets constituted one of the most critical and labor-intensive stages of the applied digitization workflow. In the examined case studies, geometric data originated from multiple acquisition sessions and sensing modalities, primarily photogrammetric reconstructions and structured light scanning outputs. While the combination of these techniques is often advocated in the literature to improve completeness and robustness, our empirical observations confirm that geometry integration represents a major source of uncertainty and error propagation in practice.

Initial alignment was performed at the level of individual datasets, ensuring internal consistency prior to any cross-source registration. Photogrammetric reconstructions corresponding to different object orientations (e.g., upper and lower surfaces) were first aligned independently and validated for internal coherence. Only after stable intra-set alignment was achieved were these datasets brought into a common reference frame. This staged approach reduced the risk of global misalignment caused by weak overlap or ambiguous correspondences between partial reconstructions.

Structured light scan meshes were treated as geometry-driven references when their coverage and surface stability allowed. However, in several specimens—particularly those with complex morphology or heterogeneous optical properties—the structured light data exhibited localized noise, missing regions, or surface distortions. In such cases, these datasets could not reliably serve as primary geometric anchors and were instead used

selectively to support global shape continuity. This observation highlights that range-based data, although often assumed to provide superior geometric accuracy, may underperform on organic or optically challenging surfaces when acquisition conditions are constrained.

Cross-modality alignment was conducted using geometry-based registration, followed by manual refinement to address residual discrepancies. Automatic registration proved sensitive to differences in sampling density, noise characteristics, and partial overlap between datasets. Even minor misalignments at this stage propagated into downstream processes, manifesting as surface discontinuities and localized tension in the merged meshes. Consequently, iterative validation and incremental adjustments were required to achieve acceptable geometric coherence.

An important empirical finding concerns the limitations of direct mesh-to-mesh fusion between independently reconstructed models. In practice, merging polygonal models generated from different sensing principles often resulted in compounded artifacts rather than improved accuracy. Differences in surface interpretation, smoothing behavior, and noise distribution hindered seamless integration and frequently necessitated extensive manual intervention. As a result, geometry integration was approached conservatively, prioritizing internal consistency and interpretability over aggressive fusion.

Overall, the alignment and integration process confirmed that hybrid digitization workflows are not inherently additive. While combining datasets can enhance completeness, it also amplifies sensitivity to acquisition inconsistencies and registration errors. Successful integration therefore depends less on the availability of multiple sensing modalities and more on controlled acquisition planning, staged alignment strategies, and explicit validation at each integration step.

3.7. Texture Mapping and Remapping Workflow

Texture mapping constituted a critical stage in the applied digitization workflow, as visual fidelity and interpretability were primary requirements for the examined cultural heritage and paleontological specimens. Unlike purely geometric reconstruction, texture quality was found to be highly sensitive to both acquisition conditions and upstream geometric reliability, making texture generation one of the most fragile components of the pipeline.

Texture projection was performed using photogrammetric image sets, mapping radiometric information onto the consolidated geometric models produced during the alignment and integration stage. In cases where geometric reconstruction was stable and dense, texture projection yielded visually coherent results with high local detail. However, when geometry exhibited noise, surface discontinuities, or incomplete regions, texture projection amplified these imperfections, resulting in a blurred appearance, local stretching, and visible seams.

Radiometric inconsistency across image sets emerged as a dominant challenge. Despite efforts to maintain stable exposure and illumination during acquisition, variations in light intensity, color temperature, and shadow distribution were unavoidable across sessions and object orientations. These variations propagated directly into the texture atlases, producing discontinuities at projection boundaries and reduced visual coherence. Multi-session acquisitions, in particular, were prone to visible transitions between texture regions, even when geometric alignment was satisfactory.

To mitigate these effects, texture remapping was performed in a staged manner. Separate texture projections were generated for different object sides or acquisition sets, prioritizing images with minimal specular response and stable illumination. These intermediate textures were subsequently merged onto the unified geometry. While this approach im-

proved local sharpness and reduced projection artifacts, it introduced additional complexity at texture boundaries, requiring manual intervention and careful parameter tuning.

A further limitation was observed in areas where photogrammetric reconstruction relied primarily on vertex color information rather than high-resolution texture maps. In such cases, increasing texture resolution did not recover lost detail, as the underlying radiometric information was already degraded. This reinforced the dependency of texture quality on acquisition and reconstruction stages rather than on projection parameters alone.

Overall, the texture mapping process highlighted that visual fidelity in applied digitization is not a downstream cosmetic step but a cumulative outcome of acquisition planning, geometric reliability, and radiometric stability. Even under controlled indoor conditions, texture artifacts were recurrent and spatially systematic, underscoring the limitations of conventional texture projection pipelines when applied to complex, organic, or optically challenging surfaces.

3.8. Post-Processing and Model Optimization

The final stage of the digitization workflow focused on post-processing and optimization of the reconstructed 3D models, aiming to balance geometric fidelity, visual clarity, and practical usability for documentation, analysis, and dissemination. This stage did not seek to "correct" upstream acquisition or reconstruction limitations but rather to manage their impact in a controlled and transparent manner. An example of the final post-processed mesh after conservative refinement is shown in Figure 5.

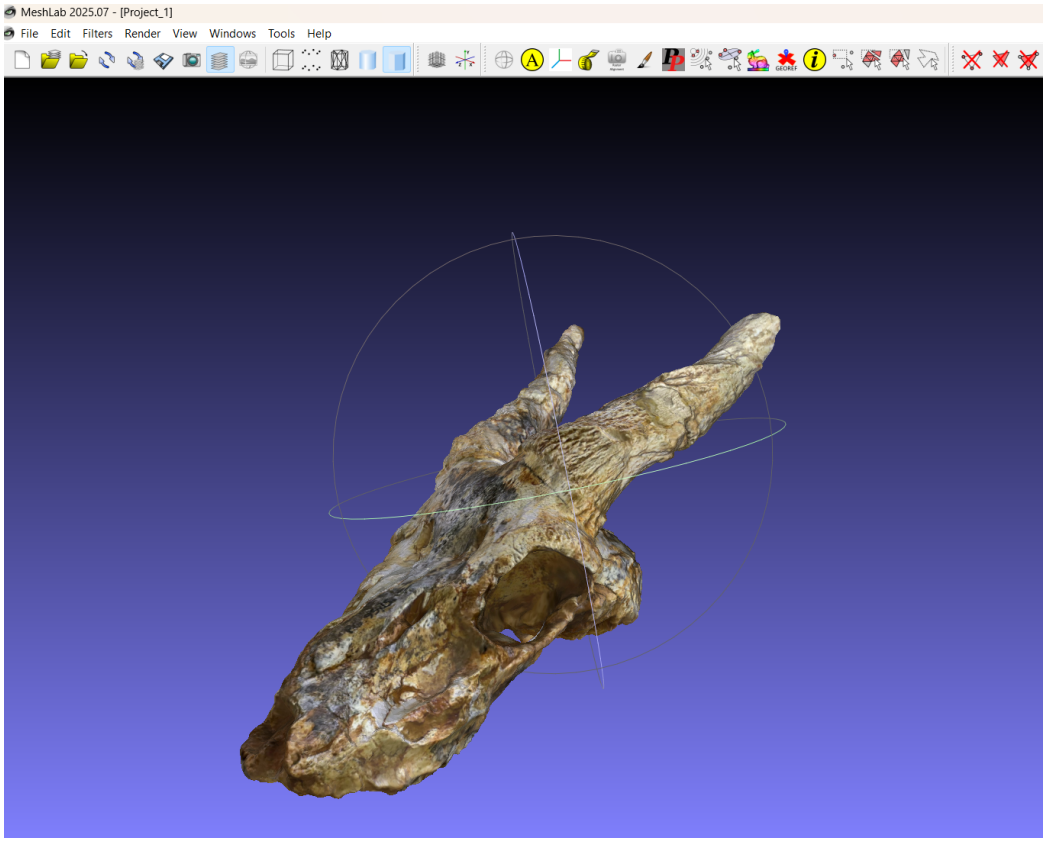


Figure 5. Final post-processed 3D model after mesh-level refinement in Meshlab.

Post-processing operations were primarily conducted at the mesh level. Background geometry introduced during acquisition and reconstruction was manually removed, and isolated components not belonging to the target object were identified and deleted. Hole filling was applied selectively and conservatively, prioritizing topological coherence while

avoiding the reconstruction of speculative or diagnostically misleading geometry. Regions known to be affected by acquisition constraints or optical instability were treated with particular caution, and aggressive automated filling was intentionally avoided.

Surface smoothing was applied sparingly to reduce high-frequency noise introduced during dense reconstruction and mesh generation. While smoothing improved visual coherence, especially for dissemination-oriented outputs, excessive application was found to obscure fine surface detail and alter morphological characteristics relevant for scientific interpretation. Consequently, smoothing parameters were adjusted on a per-object basis, and multiple intermediate versions were retained to support different use cases.

Mesh decimation was employed to produce optimized derivatives suitable for real-time visualization and online dissemination platforms. Polygon reduction was guided by curvature-aware strategies, preserving high-detail regions while simplifying flatter surfaces. This process highlighted a recurring trade-off: models optimized for interactive visualization often sacrificed subtle geometric features that were preserved in high-density reference meshes. For this reason, distinct model variants were generated, separating documentation-oriented assets from dissemination-ready representations.

Throughout post-processing, it became evident that manual intervention remained a significant component of applied digitization workflows. Automated optimization tools were effective in reducing processing time but required expert oversight to prevent the introduction of artifacts or the loss of semantically meaningful detail. Rather than eliminating manual effort, post-processing redistributed it toward decision-making and quality control.

In summary, post-processing and optimization functioned as a constraint-aware refinement stage rather than a corrective solution. The quality of the final models remained fundamentally bounded by acquisition and reconstruction conditions, reinforcing the necessity of viewing post-processing as an integrative step within the broader digitization pipeline rather than as an independent remedy.

3.9. Reconstruction Quality Assessment Criteria and Uncertainty Handling

The evaluation of reconstruction quality in this study was primarily qualitative in nature. Rather than relying on quantitative accuracy metrics (e.g., RMSE, Hausdorff distance) or direct comparisons against reference datasets (ground truth scans), the assessment focused on criteria that are more relevant to paleontological documentation and interpretive use under museum constraints. These criteria were defined in consultation with domain experts (paleontologists) and were applied consistently across cases.

Specifically, reconstruction quality was assessed according to (i) morphological readability of diagnostically relevant features (e.g., edges, ridges, concavities, thin anatomical structures), (ii) surface continuity and completeness (extent and spatial distribution of missing regions), (iii) visual coherence and absence of visually disruptive artifacts (noise, seams, distortions) that could bias observation, and (iv) radiometric reliability in texture appearance (color consistency, sharpness, limited stretching) for documentation and dissemination.

Quantitative metrological evaluation was intentionally not prioritized because the primary objective of the digitization campaigns was not absolute metric precision at surveying or engineering standards but reliable visual documentation and interpretability of complex organic specimens within realistic operational and conservation limitations (restricted access, mounting supports, and limited lighting intervention). Consequently, the workflow emphasized robust reconstruction, visual fidelity, and expert interpretability as the dominant quality targets.

Within this methodological framework, uncertainty was treated as an intrinsic outcome of applied digitization rather than as an error to be fully eliminated. Spatially systematic

ambiguities (e.g., occluded regions, optically unstable surfaces, and multi-session alignment boundaries) informed both interpretation and post-processing decisions, leading to conservative operations (selective filling, moderated smoothing, and the retention of alternative model variants) that preserve transparency about reconstruction confidence.

Although the evaluation framework was primarily qualitative, a set of semi-quantitative indicators was additionally recorded to increase methodological transparency and cross-case comparability. These included (i) number of aligned cameras and percentage of successfully aligned images per dataset, (ii) average reprojection error after tie-point filtering, (iii) dense point cloud size (number of points) and percentage of depth-map completion, (iv) mesh polygon count before and after decimation, (v) visual overlap percentage between multi-session datasets prior to ICP alignment.

These indicators were not used as strict performance benchmarks but as internal consistency measures to detect instability patterns and to compare behavior across acquisition modalities. Their inclusion strengthens reproducibility and clarifies that the observed failure modes were systematic rather than anecdotal.

3.10. Scale Definition and Geometric Consistency Control

Although metric precision was not the primary objective of the digitization campaigns, geometric scaling and dimensional consistency were treated as essential methodological components in order to ensure internal coherence and cross-modality comparability.

For photogrammetric reconstructions, scale was defined using calibrated scale bars positioned in proximity to the specimens during acquisition. In cases where the use of external markers was restricted due to conservation or exhibition constraints, direct physical measurements of stable anatomical landmarks were introduced in the reconstruction software as reference distances. These reference distances were measured using digital calipers and subsequently applied as scale constraints within the SfM bundle adjustment environment.

No adhesive targets were attached directly to the artifacts due to conservation ethics. Instead, coded or non-coded reference markers were placed on the supporting base when permitted. This approach ensured that the photogrammetric model was metrically scaled while respecting object integrity.

For structured light scanning (SLS), scale was inherently defined through the factory calibration of the system. However, cross-validation against independent physical measurements was performed to confirm dimensional stability.

To assess cross-modality geometric consistency, photogrammetric and SLS-derived point clouds were exported and compared in a common reference frame. Alignment was performed using ICP-based registration, followed by visual and local deviation inspection. While full metrological benchmarking was outside the scope of this study, comparative inspection revealed localized discrepancies primarily in concave or optically unstable regions, supporting the qualitative observations reported in Section 5.

To further examine geometric consistency between modalities, a cloud-to-cloud comparison was performed after ICP alignment. Local deviation inspection revealed that global-scale consistency was preserved within acceptable tolerance, while spatially localized deviations were concentrated in concave regions, thin morphological structures, and optically unstable surfaces. No systematic global scaling bias was detected between PG and SLS outputs. Instead, divergence patterns corresponded to modality-specific sensing limitations, reinforcing the interpretation that observed discrepancies stem from acquisition physics rather than scaling error.

4. Challenges and Pitfalls in Applied 3D Digitization

The applied digitization workflow revealed a set of recurring challenges that emerged consistently across acquisition, reconstruction, and post-processing stages. Importantly, these challenges were not isolated technical failures but systematic outcomes of operating under realistic cultural heritage constraints.

At the acquisition level, limitations in physical access, object mounting, and conservation restrictions reduced viewpoint diversity and constrained overlap. These factors directly affected both photogrammetric alignment stability and structured light scan completeness, leading to spatially consistent gaps and weakly constrained regions rather than random reconstruction noise.

Material and optical properties constituted a second major source of difficulty. Organic and paleontological specimens frequently exhibited weak texture, subtle chromatic variation, or mixed reflectance behavior, which destabilized feature matching in photogrammetry and reduced measurement reliability in structured light scanning. These effects propagated downstream, influencing dense reconstruction quality, surface noise, and texture projection fidelity.

Integration of datasets acquired across multiple sessions or sensing modalities further amplified these issues. Differences in sampling density, noise characteristics, and partial coverage limited the effectiveness of automatic registration and necessitated iterative, expert-driven refinement. In several cases, attempts at direct mesh-to-mesh fusion increased geometric inconsistency rather than improving completeness, highlighting the non-additive nature of hybrid workflows in practice.

Finally, post-processing and optimization exposed inherent trade-offs between visual clarity, geometric fidelity, and usability. While smoothing, hole filling, and decimation improved visual coherence and dissemination readiness, these operations required careful moderation to avoid masking uncertainty or altering diagnostically relevant morphology.

Collectively, these observations underline that challenges in applied 3D digitization are predominantly constraint-driven rather than tool-specific. Recognizing these pitfalls as intrinsic to real-world practice is essential for realistic planning, transparent reporting, and responsible reuse of 3D cultural heritage models.

5. Results and Empirical Observations

The applied digitization workflow produced heterogeneous results across the examined object sets, reflecting variations in object morphology, surface properties, and acquisition constraints. While complete reconstructions were achievable for several specimens, others exhibited systematic geometric and radiometric limitations that persisted throughout the pipeline, as shown in [25].

A qualitative comparison between photogrammetric and structured-light point clouds indicated that global shape consistency was generally preserved after scaling alignment, whereas local deviations were spatially correlated with material-dependent acquisition instability. In particular, concave regions and thin morphological structures exhibited greater variance between modalities, reflecting differences in sensing principles and surface response. For the specimens where the AI-assisted pathway was invoked, the SfM baseline exhibited either partial alignment collapse or fragmented dense reconstruction in diagnostically relevant regions. The AI-assisted outputs provided improved mesh continuity and visually coherent textures in those regions but introduced reduced interpretability of the failure mechanisms due to limited parameter access. This supports our framing of AI assistance as a contingency option rather than a replacement of SfM-MVS under controlled digitization practice.

Photogrammetric alignment converged successfully for the majority of image sets; however, tie point distribution was frequently uneven, with localized clusters and reduced coverage in regions characterized by weak texture or repetitive surface patterns. These effects were particularly evident in concave geometries, thin anatomical features, and areas with subtle chromatic variation. In such cases, aggressive tie point filtering led to substantial reductions in camera network density without fully stabilizing reconstruction.

Dense point cloud generation produced variable surface quality. Some specimens showed coherent surface continuity, whereas others exhibited spatially consistent noise and fragmented regions. Increasing reconstruction density parameters did not uniformly improve results and, in certain cases, amplified surface irregularities. These deficiencies propagated into subsequent mesh generation, resulting in localized roughness, incomplete regions, and topological artifacts.

Structured light scanning outputs demonstrated high local geometric detail in optically favorable areas but exhibited missing data and surface distortions on darker, semi-reflective, or optically complex regions. Coverage limitations imposed by object mounting and access constraints resulted in partial meshes that required careful alignment and selective integration. In several instances, structured light data could not be reliably used as a dominant geometric reference.

Geometry alignment across multiple acquisition sessions and sensing modalities required iterative refinement. Automatic registration was sensitive to differences in sampling density and partial overlap, and manual adjustments were necessary to achieve acceptable coherence. Attempts at direct mesh-to-mesh fusion between independently reconstructed models frequently introduced additional inconsistencies rather than improving completeness.

Texture projection outcomes closely reflected the quality of underlying geometry and acquisition radiometry. Regions associated with geometric instability consistently exhibited texture blur, stretching, or visible seams. Multi-session texture mapping improved local detail but introduced radiometric discontinuities at texture boundaries. Areas relying primarily on vertex color information did not benefit from increased texture resolution.

Post-processing and optimization improved visual coherence and usability but required careful moderation. Background removal, hole filling, smoothing, and decimation enhanced model clarity for visualization purposes, while excessive application risked obscuring fine morphological detail. Multiple optimized derivatives were therefore generated to support different use scenarios, ranging from documentation to dissemination.

Overall, the empirical observations indicate that reconstruction artifacts and limitations were spatially systematic and closely aligned with acquisition constraints, surface properties, and dataset integration complexity, rather than arising from isolated processing errors.

Table 1 summarizes the qualitative behavior observed across the applied digitization workflows, synthesizing geometric, radiometric, and procedural characteristics as they emerged during the empirical reconstruction process.

To further contextualize these observations, Table 2 consolidates the recurring failure modes identified during the applied workflow, along with their primary root causes and their sensitivity across different digitization approaches.

Table 1. Condensed qualitative comparison of photogrammetry (PG), structured light scanning (SLS), and hybrid workflows observed under applied cultural heritage constraints. Codes: ++ robust, + sensitive/conditional, −1 failure-prone; NA not applicable.

Criterion	PG	SLS	Hybrid
Overall geometric completeness	+	+	++
Local surface detail	+	+	++
Sensitivity to surface material	−1	−1	+
Sensitivity to lighting	−1	+	+
Alignment robustness	+	+	−1
Texture quality	++	NA	++
Manual intervention required	+	+	−1

Table 2. Observed failure modes in applied cultural heritage digitization, their primary root causes, and sensitivity across photogrammetry (PG), structured light scanning (SLS), and hybrid workflows. Dot code: • robust; · sensitive/conditional; ○ failure-prone; — not applicable.

Failure Mode	Primary Root Cause	PG	SLS	Hybrid
Incomplete geometry	Limited access/occlusions	·	○	·
Noisy surface	Weak texture/optical instability	·	·	·
Missing patches	Reflective/translucent/dark materials	○	○	·
Alignment instability	Low overlap/multi-session capture	·	·	○
Scale inconsistency	No scale constraints/poor control references	·	•	·
Texture blur	Illumination variability	○	—	·
Texture seams	Radiometric mismatch across sessions	○	—	·
Error propagation	Cross-sensor fusion/registration drift	—	—	○

These empirical observations reinforce the central argument of this study: applied 3D digitization outcomes are shaped as much by contextual constraints and procedural decisions as by the capabilities of the underlying technologies. Recognizing and documenting these effects is essential for realistic quality assessment and informed reuse of 3D heritage models.

6. Discussion

While individual limitations of SfM photogrammetry and structured-light scanning are well known in isolation, the contribution of this work lies in their systematic operationalization under unified, realistic museum constraints and optically challenging organic specimens. Specifically, we (i) document a cross-stage failure taxonomy spanning acquisition, alignment, meshing, and texturing (rather than focusing on a single pipeline stage), (ii) synthesize these observations into decision-support artifacts (Tables 2 and 3) with an explicit uncertainty code, and (iii) report an applied contingency pathway where AI-assisted image-based reconstruction is used selectively when conventional SfM becomes unstable. The novelty is therefore practice-oriented: we translate scattered "known problems" into a reproducible, decision-relevant framework grounded in empirical workflow behavior.

The findings of this study confirm that the performance of 3D digitization workflows in cultural heritage contexts is shaped less by the nominal capabilities of individual technologies and more by the interaction between sensing principles and real-world constraints. While many individual technical limitations discussed in this study are known in isolation, the contribution of this work lies in their systematic documentation under unified applied conditions and their synthesis into a constraint-aware decision framework. Rather than evaluating technologies in laboratory isolation, this study articulates how acquisition

physics, institutional restrictions, and material behavior interact to produce recurring and predictable failure patterns.

Table 3. Practice-oriented heuristic decision matrix for selecting digitization methods under common cultural heritage constraints, derived from the recurring failure modes (Table 2) and the qualitative assessment criteria (Section 3.9). Dot code: • robust; · sensitive/conditional; ○ failure-prone; — not applicable.

Constraint	PG	SLS	Hybrid
Limited physical access	·	○	•
Reflective/translucent surfaces	○	○	·
Unstable or mixed lighting	○	·	·
Stationary-object acquisition (move cameras; expert guideline)	•	—	·
High geometric detail required	·	•	•
High visual fidelity required	•	—	•
Multi-session acquisition unavoidable	·	·	○
Dissemination/public engagement	•	·	•
Metric documentation priority	·	•	•

Photogrammetry proved particularly sensitive to illumination variability, surface texture ambiguity, and access restrictions. While acceptable geometric reconstructions were achievable for several specimens, the stability of alignment and dense reconstruction was uneven, especially for objects characterized by subtle chromatic variation or complex organic morphology. In these cases, downstream processing could not compensate for upstream instabilities, reinforcing the notion that photogrammetric pipelines remain fundamentally acquisition-driven rather than parameter-driven.

Structured light scanning, despite its potential for high-resolution geometry, did not consistently outperform image-based methods for the examined object classes. Optical surface behavior and limited radiometric capture constrained its applicability, particularly for organic and paleontological specimens where visual appearance and fine surface cues are of primary interpretive importance. The assumption that range-based acquisition can serve as a universal geometric reference was not supported under the applied conditions of this study.

Hybrid workflows improved overall completeness in certain cases but introduced additional complexity during alignment and integration. Rather than being inherently additive, the combination of heterogeneous datasets amplified sensitivity to registration errors, sampling inconsistencies, and noise propagation. These effects underscore that integration is not merely a technical step but a methodological decision requiring explicit validation and conservative interpretation.

A key observation emerging from the texture mapping and post-processing stages is that visual fidelity cannot be treated as a downstream enhancement independent of geometric reliability. Texture artifacts consistently aligned with regions of geometric uncertainty, demonstrating that appearance quality is inseparable from acquisition and reconstruction integrity. Consequently, optimization strategies functioned primarily as constraint-aware refinements rather than corrective solutions.

Taken together, the results suggest that the gap between theoretically optimal digitization pipelines and applied practice is structural rather than incidental. This observation aligns with recent critical assessments and guidelines that emphasize context-aware decision-making and explicit documentation of limitations in cultural heritage reconstruction workflows [26]. Successful outcomes depend on acknowledging constraints as first-order design parameters and on selecting methods that are not only technically ap-

propriate but also operationally feasible. This perspective challenges technology-centric narratives and supports a more transparent, practice-oriented approach to cultural heritage digitization, where limitations are documented alongside results and uncertainty is treated as an intrinsic component of the digital surrogate.

Derivation and Scope of the Decision Matrix

Table 3 is intended as a practice-oriented heuristic rather than a prescriptive standard. The entries were derived through cross-case synthesis of the recurring failure modes reported in Table 2, grounded in the qualitative quality criteria defined in Section 3.9 (morphological readability, completeness, visual coherence, and radiometric reliability). For each constraint (rows), we examined how frequently it led to workflow-breaking failures (e.g., alignment collapse, systematic missing patches, severe texture seams) versus manageable degradations that could be mitigated through realistic interventions allowed in museum settings (e.g., lighting diffusion, acquisition restructuring, conservative post-processing).

We use a three-level code to explicitly communicate uncertainty: the first denotes "recommended" (robust under the observed constraints with limited manual intervention), the second denotes "feasible but sensitive" (results depend strongly on acquisition discipline and may degrade in predictable ways), and the third denotes "high risk" (failure-prone or requiring interventions often infeasible or ethically restricted in cultural heritage practice). The matrix is therefore a transparent summary of the empirical behavior observed in our campaigns, not an authoritative ranking independent of context. Based on the empirical observations and their interpretation, Table 3 synthesizes a practice-oriented decision matrix intended to support method selection under common cultural heritage constraints.

7. Limitations

This study adopts a practice-oriented perspective grounded in real-world cultural heritage digitization campaigns. Accordingly, its scope and evaluation logic reflect operational objectives and constraints typical of museums and controlled indoor environments, where reconstruction quality is primarily assessed through expert-informed qualitative criteria (morphological readability, visual coherence, completeness, and radiometric reliability) and where uncertainty is treated as an intrinsic outcome of applied digitization rather than an error to be fully eliminated. Within this framing, several limitations should be acknowledged when interpreting the results.

First, the findings are derived from a limited number of case studies conducted primarily in museums and controlled indoor environments. While these contexts are representative of a wide range of cultural heritage and paleontological digitization scenarios, the observations may not fully generalize to large-scale outdoor sites or highly dynamic field conditions where environmental variability is more pronounced.

Second, the analysis emphasizes qualitative and empirical observations rather than formal metrological evaluation. Although reconstruction artifacts, alignment instabilities, and texture inconsistencies were consistently observed across multiple objects and workflows, no ground-truth reference models or statistically controlled accuracy benchmarks were employed. Consequently, the reported results should be interpreted as practice-informed rather than as quantitative performance assessments.

Third, the digitization workflow relies on specific classes of hardware and software tools commonly used in applied cultural heritage practice. While the identified challenges stem from sensing principles and operational constraints rather than vendor-specific behavior, alternative equipment configurations or processing pipelines may exhibit variations in robustness and failure manifestation.

Although the presented cases derive from a specific museum context, the identified failure mechanisms are rooted in sensing principles (feature matching instability, reflectance-dependent measurement error, multi-session registration drift) and are therefore transferable to comparable cultural heritage digitization scenarios involving organic, optically heterogeneous, or access-constrained objects.

Finally, institutional and conservation constraints limit the range of possible mitigation strategies. Object repositioning, surface treatments, and extensive lighting reconfiguration were restricted or prohibited, reflecting realistic ethical and organizational boundaries rather than methodological choices. As a result, some of the documented limitations are intrinsic to cultural heritage practice and cannot be resolved through technical optimization alone.

These limitations delineate the scope of the study and reinforce its focus on applied, constraint-driven digitization rather than idealized laboratory conditions.

8. Conclusions and Future Work

This study examined the divergence between theoretically optimal 3D digitization pipelines and applied practice in cultural heritage contexts, with particular emphasis on photogrammetry, structured light scanning, and hybrid workflows. Drawing on empirical observations from real-world digitization campaigns, the paper documented recurring technical and procedural challenges that emerge under realistic acquisition constraints.

The results demonstrate that no single digitization method consistently delivers complete, artifact-free models when applied to complex cultural heritage and paleontological objects. Photogrammetry remains highly dependent on illumination stability, surface texture, and access conditions, while structured light scanning is constrained by optical surface behavior and environmental control. Hybrid workflows can improve geometric completeness in certain cases but introduce additional sensitivity to alignment instability and error propagation, often increasing manual intervention rather than reducing it.

A central conclusion of this work is that digitization outcomes are fundamentally shaped by contextual constraints rather than by tool capabilities alone. Acquisition conditions, object materiality, and institutional limitations act as first-order design parameters that determine reconstruction quality and reliability. Post-processing and optimization can mitigate some visible artifacts but cannot compensate for upstream limitations, reinforcing the need for constraint-aware planning and transparent reporting.

Future work will focus on exploring reconstruction paradigms that may offer greater robustness under non-ideal acquisition conditions, particularly in relation to appearance-driven modeling and uncertainty-aware representation. In this direction, recent work on transforming point clouds into intelligent and semantically enriched model sets highlights promising pathways for integrating uncertainty, interpretation, and conservation-oriented reasoning into 3D heritage representations [27].

In parallel, the formal documentation of confidence zones and reconstruction uncertainty within 3D cultural heritage models represents a promising direction for supporting conservation, research, and dissemination use cases. These efforts aim to complement, rather than replace, established digitization pipelines by addressing their limitations in applied settings.

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Abbreviations

The following abbreviations are used in this manuscript:

3D	Three-Dimensional
PG	Photogrammetry
SfM	Structure-from-Motion
MVS	Multi-View Stereo
SLS	Structured Light Scanning
AI	Artificial Intelligence
OBJ	Wavefront Object File Format
MTL	Material Template Library

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