# 3D Meshing of Challenging Surfaces using Gaussian Splatting

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**Abstract**

Accurate 3D reconstruction of Cultural Heritage (CH) assets remains a challenging task when scenes include complex geometries and non-Lambertian surfaces, such as dense vegetation, reflective ceramics, or polished materials, which often degrade the performance of traditional multi-view stereo (MVS) pipelines. This work investigates the potential of Mesh-In-the-Loop Gaussian Splatting (MILo), a recent extension of 3D Gaussian Splatting (3DGS) that integrates differentiable mesh extraction directly within the optimization process, enabling bidirectional consistency between volumetric and surface representations. The method is evaluated on three challenging CH datasets: a monumental *Tilia tomentosa* tree located in a UNESCO-listed urban garden, a reflective ceramic object from the Sarreguemines Earthenware Museum and the South Portal façade of the Notre-Dame Cathedral of Strasbourg. MILo-based reconstructions are compared against standard photogrammetric MVS results generated with Agisoft Metashape, using terrestrial laser scanner (TLS) point clouds as geometric reference. Quantitative accuracy assessment is performed through Multiscale Model-to-Model Cloud Comparison (M3C2), focusing on error distribution, standard deviation, outlier percentage, and preservation of fine-scale structures. Results indicate that while conventional MVS performs slightly better on stable architectural surfaces, MILo significantly improves reconstruction consistency for complex organic geometries, substantially reducing outliers and better preserving thin structures. These findings highlight the suitability of MILo for CH documentation scenarios characterized by challenging surface properties and intricate natural forms.

## 1. Introduction

Accurate 3D reconstruction of complex scenes remains an open research challenge in photogrammetry, particularly when dealing with environments characterized by dense vegetation, transparent or reflective materials, and non-Lambertian surface properties (Karami et al., 2021). Such conditions often violate the assumptions underlying standard multi-view stereo (MVS) algorithms, leading to incomplete, noisy, or geometrically inconsistent reconstructions. Occlusions, thin structures, specular reflections, and view-dependent appearance further exacerbate these limitations, reducing the reliability of conventional image-based pipelines.

These challenges are especially pronounced in the field of Cultural Heritage (CH) documentation, where objects and environments frequently exhibit exactly these problematic characteristics. Monumental trees, historic gardens, glazed architectural elements, ceramic artefacts, and polished stone surfaces represent common yet difficult targets for 3D reconstruction, as they combine complex geometries with challenging optical behavior (Mortazavi and SaadatSeresht, 2022). Despite their cultural and historical relevance, such assets are often underrepresented in high-quality digital archives due to the technical difficulties involved in their documentation. At the same time, the growing demand for the systematic digitization of CH assets has increased the need for accurate and reliable 3D models. High-fidelity geometric reconstructions are essential not only for visualization and dissemination purposes (Bitelli et al., 2017), but also for metric analyses, long-term monitoring of structural changes (Bartolini et al., 2024), and the planning of conservation, maintenance, and restoration interventions (Sagar and Harshini, 2025). In this context, limitations in reconstruction accuracy can directly affect the interpretability and practical usability of 3D models (Osadcha et al., 2025).

Recent advances in radiance field representations, such as Neural Radiance Fields (NeRFs) and 3D Gaussian Splatting (3DGS), offer promising alternatives to traditional MVS approaches. By representing scenes as radiance fields, either implicitly or through explicit volumetric primitives, and optimizing them directly from image observations, these methods show increased robustness to complex appearance effects tipically presents in challenging surfaces to reconstrct. Some initial studies have begun to investigate their metric performance, including applications of NeRFs for CH documentation (Croce et al., 2024; Murtiyoso and Grussenmeyer, 2023) and assessments of Gaussian Splatting techniques on transparent surfaces (Billi et al., 2025). However, these evaluations remain limited in scope: datasets involving challenging surfaces are highly heterogeneous, and the rapid evolution of radiance field techniques makes it difficult to draw general conclusions regarding their metric reliability. Among the most recent contributions, MILo (Guédon et al., 2025) integrates a differentiable mesh extraction framework within the 3DGS optimization loop, enforcing consistency between volumetric and surface representations and yielding geometrically accurate, lightweight meshes.

Within this context, further systematic benchmarking is required to assess the suitability of emerging radiance-field-based methods for accurate surface reconstruction in CH scenarios, particularly when compared to established photogrammetric and laser scanning workflows. This work contributes to this effort by evaluating MILo Gaussian Splatting approach on challenging CH case studies, with a specific focus on metric accuracy and detail preservation.

## 2. State of the Art

Radiance field representations introduce a paradigm shift with respect to conventional point-based 3D models. While traditional point clouds describe geometry as discrete Cartesian coordinates possibly enriched with attributes, radiance fields explicitly model the view-dependent appearance of a scene, enabling a more complete description of how light interacts with surfaces. Within this framework, scene representations can be either implicit, as in NeRF (Mildenhall et al., 2020), where geometry and appearance are encoded in a continuous volumetric function (implemented by a Multi-Layer Perceptron), or explicit, as 3DGS (Kerbl et al., 2023), where the scene is represented by a set of anisotropic 3D Gaussian primitives.

The 3DGS technique was originally introduced within the computer vision and graphics communities with the primary goal of achieving efficient and high-quality novel-view synthesis and real-time rendering. As such, early implementations were mainly optimized for visual realism and rendering performance rather than for explicit geometric accuracy or metric fidelity. In its native formulation, 3DGS outputs a radiance field composed of three-dimensional Gaussian primitives characterized by position, anisotropic covariance, opacity, color, and view-dependent appearance modeled through spherical harmonics (SH). While this representation enables visually compelling reconstructions, explicit surface geometry is not directly enforced or optimized in the original pipeline, limiting its suitability for metric reconstruction tasks.

Subsequent developments, such as SuGaR (Guédon et al., 2024) and 2D Gaussian Splatting (2DGS) (Huang et al., 2024), introduced strategies to extract mesh representations from Gaussian models, thus extending the applicability of 3DGS toward surface reconstruction. However, in these approaches mesh generation and refinement are performed only after the radiance field optimization has converged. As a consequence, no gradient information is propagated from the extracted surface back to the Gaussian parameters during training, and the Gaussian configuration is not explicitly guided toward an optimal geometric surface.

In a recent paper, Guédon et al. (2025), proposes another approach by introducing a differentiable mesh extraction framework that operates during the optimization of 3DGS representations. The proposed method is called MILo (Mesh-In-the-Loop Gaussian Splatting for Detailed and Efficient Surface Reconstruction). At each training iteration, MILo differentiably extracts a mesh (vertex positions and connectivity) directly from the Gaussian parameters. This allows the gradient to flow from the mesh to the Gaussians, promoting bidirectional consistency between the volumetric (gaussian model) and surface (extracted mesh) representations. The result is a Gaussian configuration that is better suited to surface reconstruction, generating higher-quality meshes with far fewer vertices, making reconstructions more practical for downstream applications such as physical simulations and animations.

In this work, we applied MILo to different challenging surfaces in order to quantitatively evaluate whether it reconstructs fine details and non-Lambertian effects better than standard MVS outputs.

## 3. Avaiable Datasets

The main datasets are presented in Figure 1. They include an existing dataset of the winter garden of the Earthenware Museum of Sarreguemines (France), a *Tilia tomentosa* tree acquired in the University Gardens of Strasbourg (France), located within the UNESCO World Heritage Site of Neustadt, and the South Portal façade of the Notre-Dame Cathedral of Strasbourg (France).

The Sarreguemines winter garden dataset was reused from a previous study (Girardet et al., 2019) and consists of 270 RGB images acquired with a professional-grade camera (Canon EOS 5DSR). This dataset includes reflective ceramic objects and complex indoor elements and was therefore employed to assess the robustness of the reconstruction methods with respect to non-Lambertian surfaces, where reflections and specular effects significantly hinder reliable geometry and appearance reconstruction.

The tree dataset was specifically selected to evaluate performance on highly complex natural geometries, characterized by a dense network of thin branches and foliage, which makes accurate geometric reconstruction particularly challenging. For this dataset, a total of 90 RGB images were acquired using a consumer-grade smartphone (Samsung Galaxy A71, SM-A715F). The deliberate use of low-cost, widely accessible acquisition equipment was intended to assess whether satisfactory reconstruction results can be achieved even under extremely challenging geometric conditions using hardware that is readily available to the general public.

The third dataset, concerning the South Portal façade of Notre-Dame Cathedral in Strasbourg (France), was acquired as a new dataset comprising 55 images captured with a professional camera (Canon EOS R5). In this case, the aim is to evaluate the capabilities of MILo compared to the MVS technique in reconstructing carved surfaces and fine architectural details at a larger scale. For all datasets, the RGB images were accompanied by a reference point cloud acquired using a

Figure 1. The three datasets used for MILo evaluation: (left) Winter garden, Sarreguemines, Strasbourg (France); (centre) *Tilia tomentosa* tree (France) and (right) South Portal façade of the Notre-Dame Cathedral of Strasbourg (France).

terrestrial laser scanner (TLS), which was used as ground truth for quantitative evaluation. All analyses and experiments were conducted on the same hardware configuration to ensure consistency across evaluations. Specifically, tests were performed using an NVIDIA GeForce RTX 4090 GPU (24 GB VRAM, and an AMD Ryzen 9 7950X 16-Core CPU.

# 4. Methodology

The analysis involves a geometric comparison which begins with a common input: camera orientation parameters (both internal and external) along with the sparse point cloud generated through SfM performed using Agisoft Metashape v.2.0.0. This ensures a consistent reference system for both parallel reconstruction processes, which were then processed simultaneously through two independent pipelines.

The first employs traditional MVS algorithms to generate a dense point cloud, which is subsequently meshed to produce a complete 3D surface model. The second leverages the MILo framework, where 3D Gaussian ellipsoids are characterized by attributes such as position (means μ), scale, rotation, color, SH and opacity.

The MVS and MILo-generated meshes are then subjected to comprehensive comparison, using the TLS point cloud as ground truth inside CloudCompare v.2.13.2 software, using Multiscale Model to Model Cloud Comparison (M3C2) analysis including:

- Qualitative visual comparison of mesh.
- Quantitative evaluation of mesh complexity (mean, standard deviation, outliers).

Both reconstruction pipelines were configured with comparable processing settings (e.g., medium resolution for mesh reconstruction) to ensure a fair and consistent comparison.

# 5. Results and Discussion

The final results demonstrate the effectiveness of the MILo framework through qualitative and quantitative evaluation on all datasets.

## 5.1 Sarreguemines

The quantitative (Table 1), and qualitative (Figures 2 and 3) results on the Sarreguemines dataset show comparable performance between the two methods from a quantitative perspective, with Metashape slightly superior recording a standard deviation of 0.20 cm and an outlier percentage of 3.17%, compared to 0.30 cm and 8.21% for MILo. The mean error is null for both (0.00 cm), indicating the absence of systematic bias in the reconstructions. Regarding computational efficiency, Metashape demonstrates substantially faster processing, completing the reconstruction in 4.50 minutes compared to MILo's 163.34 minutes, representing approximately a 36-fold difference in processing time.

| Sarreguemines | Mean Error (cm) | St. Dev. (cm) | Outliers (%) | Time processing (min) |
|---|---|---|---|---|
| MILo | 0.00 | 0.30 | 8.21% | 163.34 |
| Metashape | 0.00 | 0.20 | 3.17% | 4.50 |

Table 1. Quantitative metrics extracted using M3C2 for Sarreguemines.

The analysis of the M3C2 deviation maps reveals that both methods tend to concentrate the major deviations in the geometrically complex areas of the fountain, particularly in the carved ornamental details where red-orange colorations indicate deviations in the order of ±(0.50-1.00) cm are observed (Figure 2). The flat architectural surfaces instead maintain

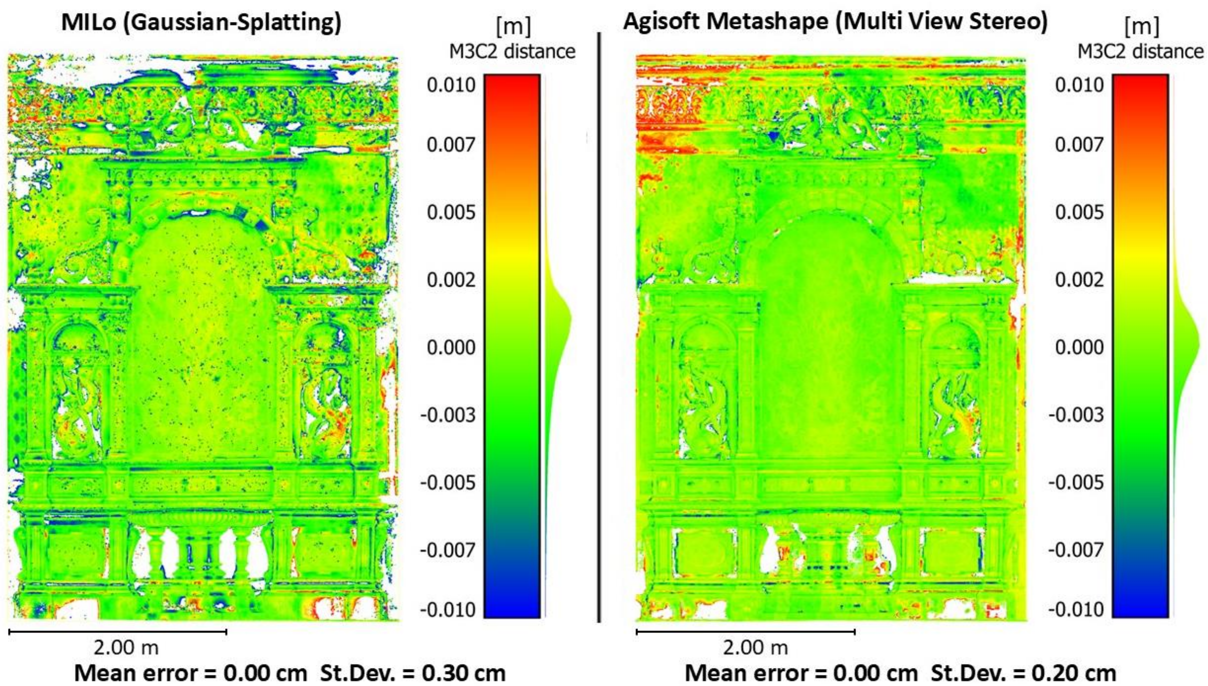


Figure 2. M3C2 distance comparison between Metashape and GS-MILo for Sarreguemines dataset against TLS reference.

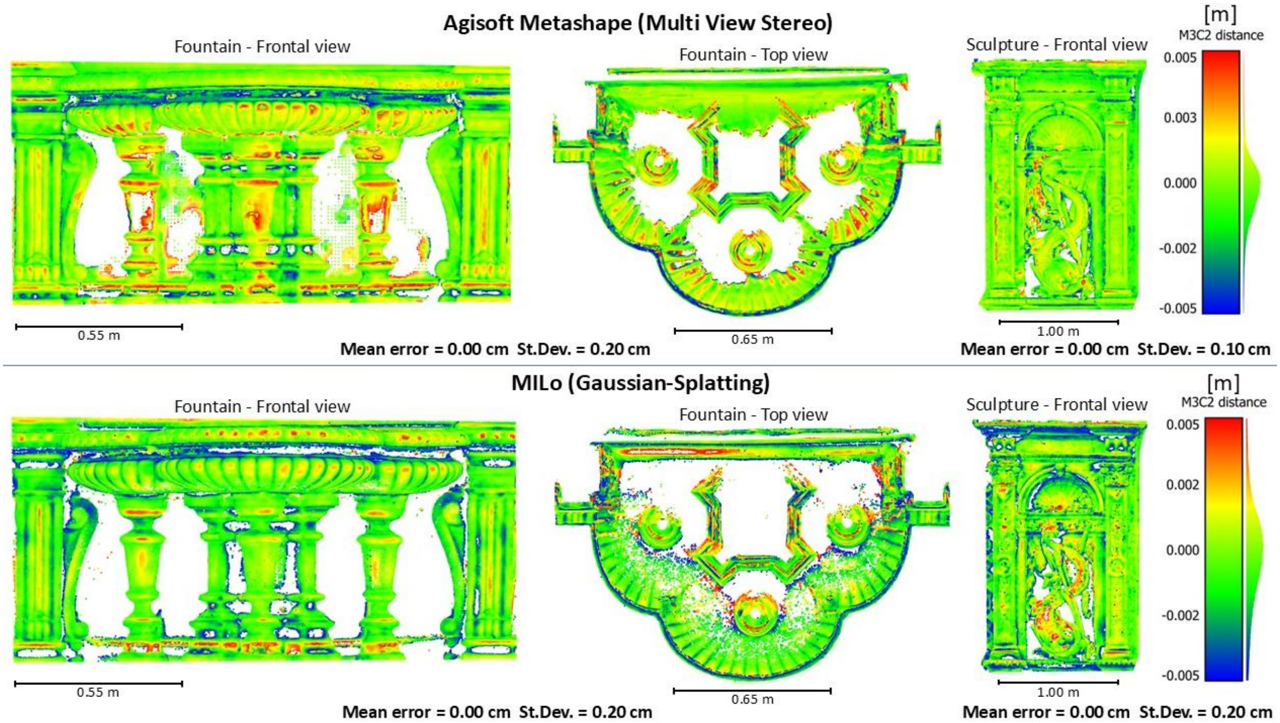


Figure 3. M3C2 distance comparison between Metashape and GS-MILo for details of Sarreguemines dataset against TLS reference.

excellent accuracy, evidenced by the predominant green coloration with deviations close to zero. Metashape appears to show slightly superior surface continuity in the decorative zones, while MILo presents greater colour variation that could suggest minor surface irregularities of approximately 0.20-0.30 cm. The histogram distributions confirm this trend: Metashape shows a tighter distribution centered at zero, while MILo presents more pronounced tails, consistent with the 0.10 cm higher standard deviation.

A particularly interesting observation emerges from the analysis of the cylindrical columns supporting the balustrade (Figure 3). Metashape, despite globally better statistics and significantly faster processing time, appears to show more extensive empty areas on the circular columns, suggesting possible difficulties in completely reconstructing these surfaces. This could be characteristic of traditional MVS approaches that depend on dense image matching and might encounter difficulties with uniform cylindrical surfaces where distinctive textures are limited. MILo, on the contrary, appears to present the same columns more completely, with predominantly green coloration and apparently reduced empty areas. This could suggest a possible advantage of the Gaussian Splatting approach in handling continuous curved surfaces, where the volumetric representation might allow better reconstruction even with partial visual information. While MILo requires substantially longer processing time, this investment appears to yield benefits in geometric completeness for specific challenging surface types such as smooth cylindrical elements.

## 5.2 Tilia tomentosa

The results on the *Tilia tomentosa* dataset (Figure 4 and Table 2) reveal a notably different performance pattern compared to the architectural case of Sarreguemines, highlighting how the nature of the reconstructed object significantly influences the comparative effectiveness of the two methods. While Metashape showed slightly superior statistics on the fountain (0.20 cm standard deviation, 3.17% outliers), the situation appears to reverse dramatically for the tree, where MILo demonstrates substantially better performance with a standard deviation of 2.80 cm and 15.18% outliers, compared to Metashape's 3.50 cm and 54.87% outliers. The mean error remains close to zero for both methods (MILo: -0.20 cm, Metashape: 0.00 cm), indicating minimal systematic bias. Regarding processing time, Metashape completed the reconstruction in only 0.70 minutes, while MILo required 84.33 minutes, representing approximately a 120-fold difference in computational time.

The visual analysis of the M3C2 deviation maps provides crucial insights into this performance difference. For MILo, the tree crown reconstruction shows predominantly green coloration across the entire canopy structure, indicating deviations generally within a ±4.00 cm range, with good coverage and continuity throughout the foliage volume. The distribution appears relatively uniform, suggesting that the method maintains consistent accuracy across different parts of the tree structure, from the denser interior branches to the peripheral foliage. The lateral and top slices views confirm this completeness, showing a well-defined tree volume with minimal data gaps even in the complex interior structure where branches overlap and create challenging occlusion patterns.

| Tilia tomentosa | Mean Error (cm) | St. Dev. (cm) | Outliers (%) | Time processing (min) |
|---|---|---|---|---|
| MILo | -0.20 | 2.80 | 15.18% | 84.33 |
| Metashape | 0.00 | 3.50 | 54.87% | 0.70 |

Table 2. Quantitative metrics extracted using M3C2 for *Tilia tomentosa*.

Metashape's reconstruction, conversely, presents a markedly different pattern. The M3C2 maps show extensive empty areas throughout the canopy, indicating significant regions where the reconstruction failed to generate geometry or where the deviations exceed the ±8.00 cm threshold. The green areas that do exist appear more fragmented and concentrated primarily in the outer periphery of the canopy where leaves are more clearly visible and less occluded. The top and lateral slices views reveal a sparse, discontinuous reconstruction with large voids in the interior and middle sections of the crown. This pattern suggests that the traditional MVS approach encounters significant difficulties with the complex and overlapping geometry of tree foliage, where individual leaves create intricate occlusion patterns and where texture repetition (similar-looking leaves) makes reconstruction particularly challenging.

The substantially higher outlier percentage for Metashape (54.87% versus 15.18%) is particularly notable and appears to reflect these extensive reconstruction gaps rather than necessarily indicating gross geometric errors where data exists.

edges, corners, and varied textures, this approach excels. However, tree canopies present multiple challenges: leaves are small, numerous, and visually similar to each other (creating ambiguous matches); they overlap extensively creating complex occlusion patterns. These factors can cause dense image matching algorithms to fail or produce unreliable matches, resulting in sparse or incomplete reconstructions.

MILo's Gaussian Splatting approach, conversely, appears to handle these challenges more effectively. The volumetric, continuous nature of the Gaussian representation might allow the method to better model, overlapping structure of foliage. Rather than requiring explicit point-to-point correspondences, Gaussian Splatting optimizes a continuous volumetric representation that can interpolate and blend information across views more fluidly. This could explain why MILo achieves more complete coverage throughout the canopy volume, including interior regions where traditional MVS struggles. The

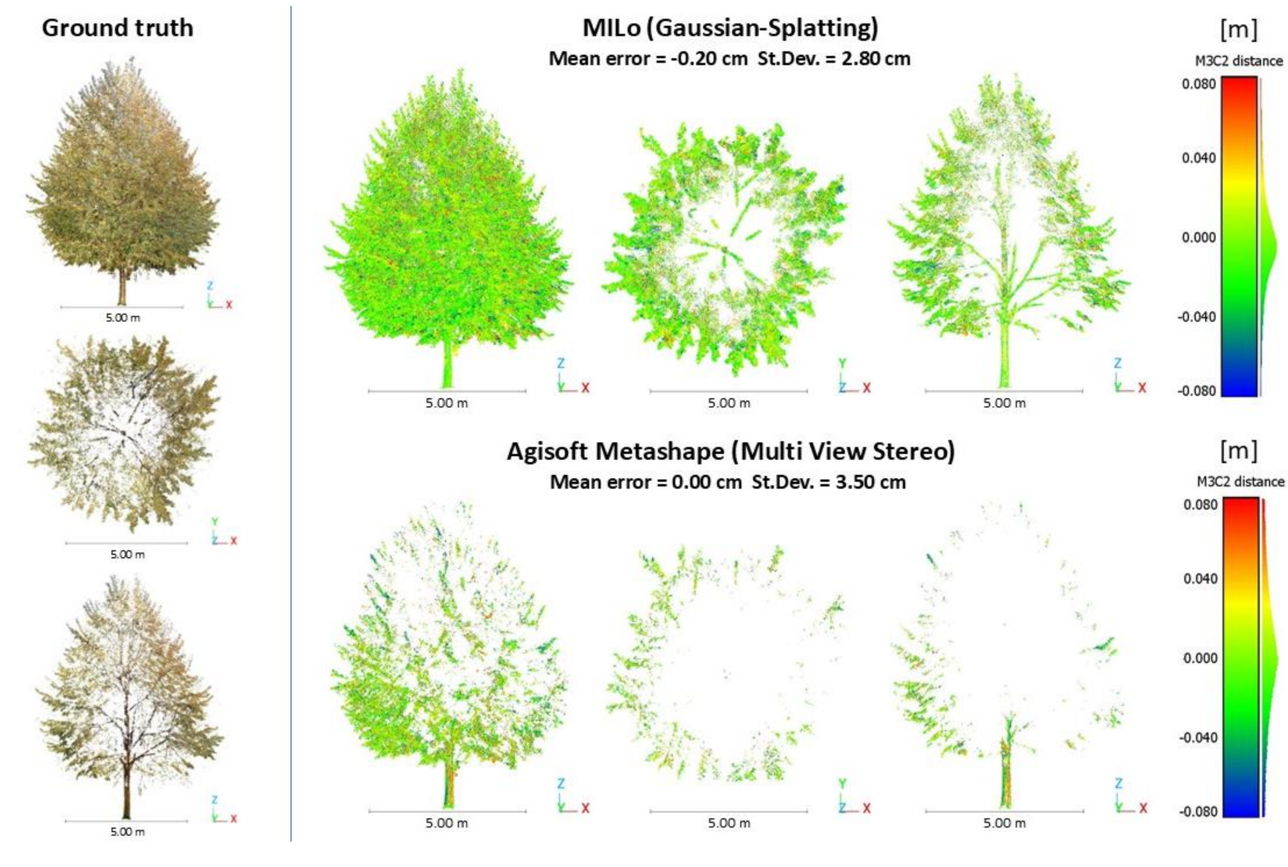


Figure 4. M3C2 distance comparison between Metashape and GS-MILo for *Tilia tomentosa* dataset against TLS reference.

In M3C2 analysis, points that fall outside the specified distance range or where no correspondence can be established are typically classified as outliers. The visual evidence suggests that much of Metashape's high outlier rate may stem from incomplete reconstruction rather than systematic mismeasurement, which would be consistent with the challenges MVS faces in geometrically complex natural structures with repetitive textures.

This performance difference could be attributed to several fundamental characteristics of the two approaches. Traditional MVS methods like those employed by Metashape rely heavily on establishing reliable correspondences between discrete points across multiple views. In architectural scenes with distinct

0.70 cm difference in standard deviation (2.80 cm for MILo versus 3.50 cm for Metashape) is also notable, though perhaps less dramatic than the outlier difference. This suggests that even in regions where both methods successfully reconstruct geometry, MILo maintains slightly more consistent accuracy. However, it's important to contextualize these values within the ±8.00 cm analysis range, which was established to account for natural movement and the inherent challenges of comparing dynamic organic structures. The substantially longer processing time required by MILo (84.33 minutes versus 0.70 minutes) represents a significant computational investment. The reduction of outliers from 54.87% to 15.18% and the improvement in standard deviation from 3.50 cm to 2.80 cm indicate that MILo provides substantially more complete and consistent geometric coverage for this complex organic structure. For applications requiring comprehensive documentation of heritage trees or dense vegetation, where geometric completeness is critical, the extended processing time may represent an acceptable trade-off for the substantial gains in reconstruction quality.

### 5.3 Notre-Dame of Strasbourg

The results on the Notre-Dame of Strasbourg dataset (Figure 5 and Table 3) reveal a markedly different performance pattern compared to both previous datasets, as the two methods achieve virtually identical quantitative metrics across all measured parameters. Both MILo and Metashape record a mean error of 0.00 cm and an identical standard deviation of 3.00 cm, indicating equivalent geometric accuracy and the absence of any systematic bias in either reconstruction. The outlier percentages are likewise comparable, with Metashape producing a marginally lower rate (66.62%) versus MILo (68.40%), a difference too small to be considered practically significant. The most striking divergence between the two methods remains, as observed in previous cases, the processing time: Metashape completed the reconstruction in 5.58 minutes, while MILo required 283.71 minutes, representing an approximately 50-fold difference in computational cost.

The visual analysis of the M3C2 deviation maps largely corroborates this statistical equivalence, though with some noteworthy spatial differences in error distribution. Both reconstructions display a predominantly green coloration across the main facade surfaces, indicating that deviations generally fall within the ±2.50 cm range for the large flat and moderately detailed areas such as the central nave wall and the lower register. However, both maps also share similar zones of elevated deviation: the upper lateral towers and pinnacles, the sculptural reliefs of the central portal, and the rose window surround all exhibit warmer yellow and orange tones, reflecting the geometric complexity and fine detail density of these elements. In MILo's reconstruction, a notable concentration of red coloration is visible in the upper central gable area, suggesting local deviations approaching or exceeding ±8.00 cm in that region, a pattern less pronounced in the Metashape result. Conversely, Metashape's results (Figure 5), presents a slightly more fragmented distribution of white voids, particularly around the pinnacles and lateral towers, indicating localized reconstruction gaps in the most geometrically intricate areas.

| Notre-Dame of Strasbourg | Mean Error (cm) | St. Dev. (cm) | Outliers (%) | Time processing (min) |
|---|---|---|---|---|
| MILo | 0.00 | 3.00 | 68.40% | 283.71 |
| Metashape | 0.00 | 3.00 | 66.62% | 5.58 |

Table 3. Quantitative metrics extracted using M3C2 for Notre-Dame of Strasbourg.

This convergence in overall performance between the two methods for a large Gothic architectural facade can be attributed to the nature of the subject itself. Unlike the tree canopy, which posed fundamental challenges for MVS due to repetitive textures, or the fountain, with reflective surfaces, Notre-Dame presents a scene that is simultaneously large-scale and highly detailed. The facade provides an abundance of distinct, high-contrast features, carved stone ornaments, pointed arches and mullioned windows, that enable reliable feature matching for Metashape's MVS pipeline. At the same time, the scale and structural regularity of the building provide sufficient geometric constraint for MILo's Gaussian Splatting optimization to

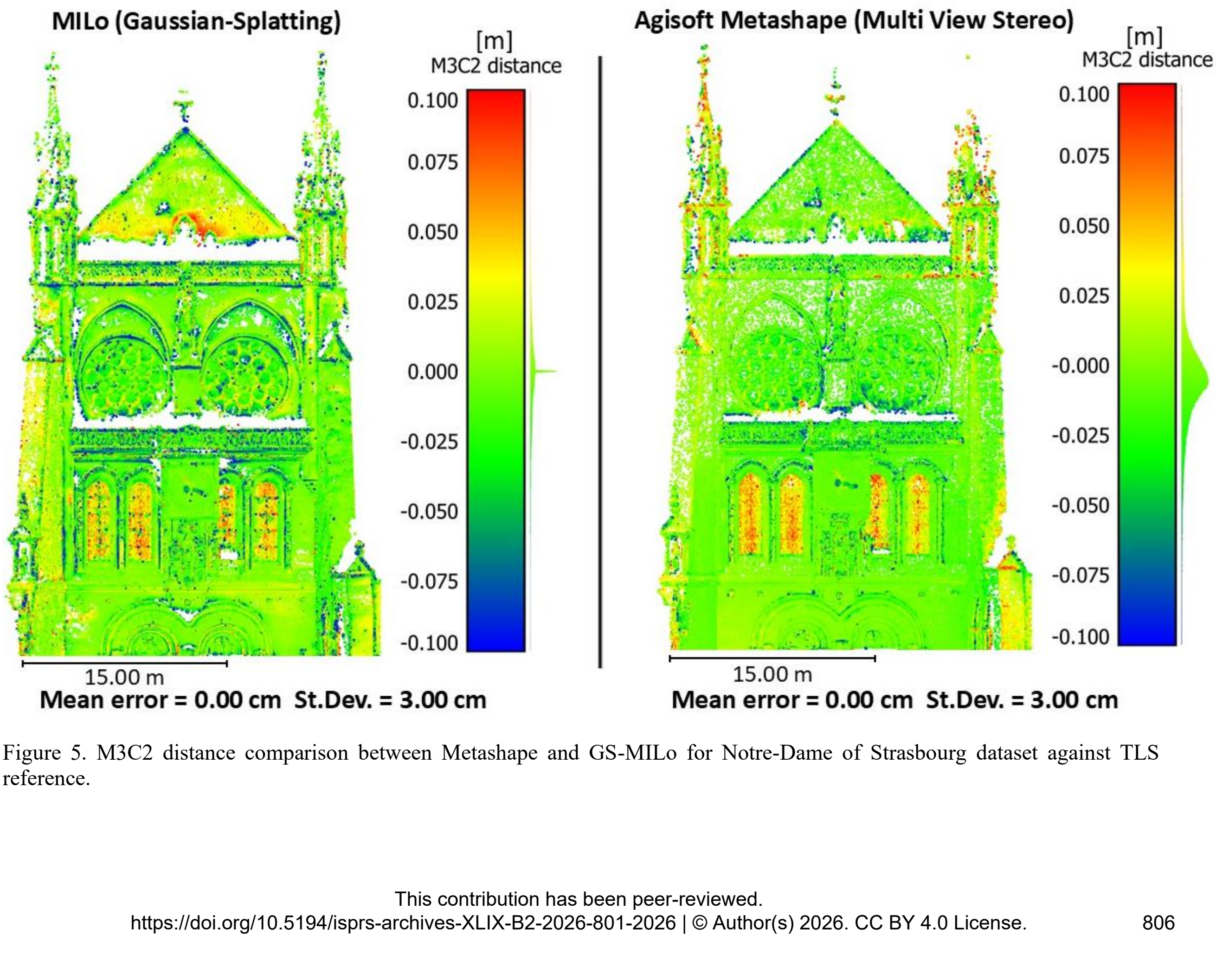


Figure 5. M3C2 distance comparison between Metashape and GS-MILo for Notre-Dame of Strasbourg dataset against TLS reference.

converge accurately. The result is a case where neither method holds a clear advantage in terms of geometric fidelity, and the choice between them would therefore be driven primarily by practical considerations, most notably the substantial difference in processing time, which strongly favors Metashape when reconstruction completeness and accuracy are demonstrably equivalent.

## 6. Conclusions

This study investigated the potential of MILo for accurate 3D reconstruction of complex CH surfaces, comparing its performance with traditional MVS approaches implemented in Metashape. Three distinct datasets were analyzed: the Sarreguemines winter garden, characterized by reflective ceramic objects and architectural elements; a monumental *Tilia tomentosa* tree representing a highly complex organic geometry with dense foliage; and the façade of Notre-Dame of Strasbourg, representing a large-scale Gothic architectural structure with rich sculptural detail. Quantitative evaluation was performed using M3C2 analysis, employing high-precision TLS point clouds as ground-truth reference data.

These results collectively suggest that the continuous and volumetric representation of Gaussian Splatting, combined with MILo's differentiable mesh extraction framework, may offer significant advantages for reconstructing complex organic geometries where traditional MVS algorithms struggle. Conversely, for rigid, well-textured architectural surfaces, whether at the scale of a decorative ceramic fountain or a monumental cathedral façade, traditional MVS approaches remain highly competitive and achieve comparable or slightly better accuracy with markedly superior computational efficiency.

From a practical CH documentation perspective, the reduction in outliers from 54.87% to 15.18% for organic geometries represents a significant advantage for applications such as vegetation monitoring in historic gardens or the documentation of monumental trees. For large architectural structures such as Notre-Dame, where both methods yield equivalent geometric fidelity, the substantially lower computational cost of MVS makes it the preferred choice for routine documentation workflows. The methodological selection should therefore be guided by the nature of the asset to be documented: when addressing complex organic geometries, the investment in longer computation times with MILo is justified by the gains in reconstruction completeness; when surfaces are predominantly architectural and well textured, Metashape represents the more efficient solution without sacrifice in accuracy.

Several limitations must be acknowledged. The analysis was conducted on only three datasets, and while these cover a meaningful range of CH asset typologies, the relatively controlled acquisition scenarios limit the generalizability of the findings. The substantial difference in processing times, with MILo requiring between 50 and 120 times longer than Metashape across the three datasets, remains an important practical constraint. Future research should extend the evaluation to more diverse scenarios including heavily occluded structures, and assets with mixed organic and architectural components. Optimizing the computational efficiency of MILo constitutes a critical area for further development.

In conclusion, this preliminary investigation suggests that MILo represents a promising alternative for the reconstruction of complex organic geometries in CH, albeit at the cost of substantially increased computational effort. The optimal methodological choice depends on the application context and the geometric nature of the subject: for complex organic structures, MILo offers substantial advantages in reconstruction completeness that justify longer processing times; for architectural surfaces, regardless of their scale or decorative complexity, traditional MVS approaches remain competitive and considerably more efficient.

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