RGNZ/MGPB

Rudarsko-geološko-naftni zbornik
(The Mining-Geology-Petroleum Engineering Bulletin)
DOI: 10.17794/rgn.2026.1.6

Original scientific paper

# Assessing the Feasibility of Photogrammetry for Underground Mine Monitoring: A Simulation-Based Study

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**Abstract**
Underground mining operations face significant challenges in monitoring structural stability and safety due to limited visibility and access. This study evaluates the feasibility of photogrammetry for underground mine monitoring using a simulation-based framework, bypassing resource-intensive field experiments. Synthetic datasets, generated via Blender and MATLAB, were used to assess photogrammetric accuracy, scalability, and limitations under varying lighting (25–100 lux), noise, and dust conditions. Three Structure-from-Motion (SfM) algorithms – COLMAP, OpenMVG, and Agisoft Metashape – were compared to evaluate performance robustness. The results indicate a Root Mean Square Error (RMSE) of 2.3 cm for COLMAP at 50 lux, improving to 1.9 cm at 100 lux, with OpenMVG and Agisoft Metashape showing comparable accuracy (RMSE 2.1–2.5 cm) but varying processing times. Challenges persist in low-light conditions (RMSE 3.8 cm at 25 lux) and complex geometries, exacerbated by simulated dust (RMSE 2.5 cm), highlighting the need for supplemental lighting and advanced image preprocessing. Point density ranged from 8,500 to 12,300 points/m$^2$, with dust and noise reducing detail retention. These findings suggest photogrammetry's potential as a cost-effective, non-invasive monitoring tool, complementing traditional methods like Light Detection and Ranging (LiDAR). The simulation-based approach provides a scalable framework for optimizing photogrammetric workflows, supporting Industry 4.0 trends in mining safety and efficiency. Future work should validate these results in real-world conditions to address environmental variables like dust and humidity.

**Keywords:**
photogrammetry; underground mining; simulation; 3D modelling; mine monitoring; safety

## 1. Introduction

Underground mining, critical for global resource extraction, faces significant challenges in ensuring operational safety and efficiency due to limited subsurface monitoring capabilities. Issues such as rock mass instability, tunnel convergence, and gas accumulation frequently cause operational delays or catastrophic failures (**Hoek and Brown, 1980**). Conventional monitoring methods, including laser scanning and manual surveys, while accurate, are often resource-intensive and impractical for real-time application in inaccessible areas (**Meaka and Vokain, 2023**).

Photogrammetry, widely utilized for surface mapping, remains underexplored in underground environments due to constraints like poor lighting and confined spaces (**Remondino and El-Hakim, 2006**). This study introduces a novel simulation-based methodology to evaluate photogrammetry's feasibility for underground mine monitoring, eliminating the need for costly and logistically complex field experiments. By employing computational tools such as Blender and Matrix Laboratory (MATLAB) to create synthetic underground scenes, we assess photogrammetry's theoretical performance under controlled conditions. The objectives are threefold:

1. to determine the precision of photogrammetric reconstruction, including comparisons of Structure-from-Motion (SfM) algorithms (COLMAP, OpenMVG, Agisoft Metashape),
2. to identify critical environmental and technical factors influencing its efficacy, and
3. to propose a practical framework for integrating photogrammetry into mining engineering workflows.

This approach aligns with Industry 4.0 trends in mining, emphasizing digital twins, remote sensing, and automated monitoring to enhance safety and efficiency (**Lillesand et al., 2015**). The paper is organized as follows:

- Section 2 reviews photogrammetric principles and its limited mining applications.

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Received: 24 June 2025. Accepted: 18 August 2025.

- Section 3 outlines the simulation methodology.
- Section 4 presents results with supporting visuals.
- Section 5 discusses findings; and
- Section 6 concludes with implications and future directions.

The paper includes **Figures 1–6**, which illustrate the synthetic mine model, error distribution, and visual synthesis of photogrammetry's performance under varying conditions, and **Tables 1–6**, which present simulation parameters, error metrics, environmental impacts, computational performance, and scalability comparisons.

## 2. Background and Literature Review

Photogrammetry relies on the principle of triangulation to reconstruct three-dimensional (3D) geometry from overlapping two-dimensional (2D) images (**Mikhail et al., 2001**). Advances in Structure-from-Motion (SfM) algorithms, such as COLMAP, OpenMVG, and Agisoft Metashape, have made it a cost-effective alternative to Light Detection and Ranging (LiDAR) for surface mine mapping, achieving accuracy below 5 cm in optimal conditions (**Westoby et al., 2012**). However, underground applications are scarce due to challenges like insufficient lighting, dust interference, and restricted camera placement (**Donovan et al., 2016**).

Studies such as **Eberhardt (2012)** have demonstrated photogrammetry's potential in small-scale tunnel mapping, but scalability to complex mine networks remains untested. Photogrammetry has been effectively applied in geotechnical monitoring, such as landslide displacement analysis using unmanned aerial systems, demonstrating its versatility for spatial data collection in challenging environments (**Jakopec et al., 2022**).

Recent advancements have begun to address these challenges, particularly through the integration of photogrammetry with other technologies and simulation-based methodologies. For instance, **Benton et al. (2017)** conducted a case study at the Lucky Friday mine, demonstrating the use of photogrammetry to monitor ground control in underground entries. Their work highlighted the ability of photogrammetric surveys to augment traditional crack meter measurements, achieving high accuracy in tracking deformation with a 3D point cloud scaled to global coordinates. This approach provides a more comprehensive tensor description of ground movement compared to vector-based conventional methods, offering deeper insights into rock mass behavior under high-stress conditions. However, the study also noted limitations in low-light environments, reinforcing the need for supplemental lighting strategies in underground settings.

Mining engineering demands precise, scalable monitoring tools. Current methods – geodetic surveys, extensometers, and LiDAR – provide high accuracy but require significant setup time and expertise (**Dunnicliff, 1993**). Simulation-based studies offer a workaround, allowing researchers to model complex scenarios without physical constraints (**Ozdemir and Kumral, 2019**). For example, **Chimunhu et al. (2022)** reviewed the application of machine learning in underground mine planning and scheduling, emphasizing the role of simulation in handling large datasets and complex constraints. While their focus was on production optimization, their findings underscore the broader potential of simulation-based approaches in addressing operational challenges, such as those encountered in photogrammetric monitoring.

Emerging technologies are also enhancing photogrammetry's applicability in underground mining. **Ristović and Vulić (2014)** explored affordable photogrammetry for 3D modelling of underground mining transportation systems, using a standard digital camera and open-source software. Their study, conducted as part of a student project at the University of Ljubljana, achieved sufficient accuracy for practical applications while highlighting the method's cost-effectiveness and accessibility. However, the authors noted that lighting conditions and camera placement remain significant barriers, particularly in confined spaces with irregular geometries. **Ferrero et al. (2009)** investigated the use of photogrammetry in monitoring surface subsidence caused by underground mining, combining unmanned aerial vehicle (UAV)-based photogrammetry with traditional surveying methods. Their findings suggest that photogrammetry can achieve sub-centimeter accuracy in deformation monitoring, even in challenging terrains, but requires careful calibration and environmental control to mitigate errors from dust and variable lighting.

The integration of photogrammetry with other sensing modalities is another promising direction. **Chen et al. (2023)** evaluated the ecological environment quality in the Juye mining area using active-passive remote sensing, combining photogrammetry with satellite imagery to assess post-mining restoration. While their study focused on surface impacts, their methodology of integrating multiple data sources could be adapted for underground monitoring, potentially addressing photogrammetry's limitations in low-visibility environments. Such hybrid approaches are increasingly advocated in mining research, as they offer a more robust framework for capturing the multifaceted nature of subsurface conditions (**Lillesand et al., 2015**).

Recent advancements have begun to address these challenges, particularly through the integration of photogrammetry with other technologies and simulation-based methodologies. This study builds on these foundations, using synthetic datasets to explore photogrammetry's adaptability to underground conditions. Despite these advancements, gaps remain in the application of photogrammetry to underground mining. Most studies focus on small-scale or surface applications, with limited exploration of large-scale underground networks. Moreover, while simulation-based studies provide valuable insight, they often oversimplify real-world variables such as dust, humidity, and dynamic lighting changes, which can significantly impact photogrammetric accuracy (**Donovan et al., 2016**). This study builds on these foundations, using synthetic datasets to explore photogrammetry's adaptability to underground conditions. By evaluating tools like COLMAP alongside potential comparisons with OpenMVG and Agisoft Metashape, it aims to bridge these gaps through a controlled simulation environment, providing a foundation for future field validations. It aims also to bridge these gaps by using a controlled simulation environment to systematically evaluate photogrammetry's performance under varying underground conditions, providing a foundation for future field validations. This work aligns with Industry 4.0 trends in mining, supporting the adoption of automated, data-driven monitoring systems for enhanced operational efficiency.

Recent studies have further explored photogrammetry's integration with emerging technologies, such as machine learning for feature detection and hybrid sensing with LiDAR, to overcome underground challenges (**e.g. Chen et al., 2023**). These advancements highlight the growing interest in photogrammetry as a versatile tool for mining applications, yet systematic evaluations of its scalability and robustness in large-scale underground networks remain limited, a gap this study aims to address through simulation.

Building on these insights and addressing the gap in systematic evaluations of photogrammetry's scalability for large-scale underground networks, this study employs a simulation-based methodology to assess its theoretical feasibility under controlled mining conditions.

## 3. Methodology

This section outlines the simulation-based methodology to evaluate photogrammetry's feasibility for underground mine monitoring. The approach leverages computational tools to create synthetic underground scenes, enabling controlled testing of photogrammetric performance without the logistical challenges of field experiments. The workflow, summarized in **Figure 2**, includes simulation design, synthetic image generation, photogrammetric processing, and evaluation metrics, with a focus on environmental factors like dust.

### 3.1. Simulation Design

A synthetic underground mining environment was developed using Blender 3.6, a three-dimensional (3D) modelling software, and Matrix Laboratory (MATLAB) R2023a for data processing. The model represents a 100 m × 50 m × 20 m tunnel network with irregular rock surfaces and mining equipment (e.g. vehicles, rail tracks), mimicking realistic subsurface geometry (see **Figure 1**). Texture variations and lighting conditions were controlled to replicate low-light scenarios typical of underground mines, ensuring alignment with real-world constraints (**Donovan et al., 2016**).

### 3.2. Synthetic Image Generation

A virtual camera with a 12-megapixel sensor and 50 mm focal length was positioned at 5 m intervals along the tunnel, capturing 50 overlapping images with 70% overlap, as recommended for robust SfM reconstruction (**Westoby et al., 2012**). The 12-megapixel resolution balances detail capture with computational efficiency, reflecting mid-range industrial cameras used in mining (**Ristović and Vulić, 2014**). Lighting was simulated using a diffuse source at 50 lux, typical of underground conditions (**Donovan et al., 2016**). Gaussian noise ($\sigma$=0.01) was added to images to simulate real-world imperfections (**Hartley and Zisserman, 2004**).

**Figure 1.** Synthetic underground mine model used for photogrammetric simulation. The 100 m x 50 m x 20 m tunnel network features irregular rock surfaces, mining equipment, and a diffuse lighting gradient (50 lux at center). Red dots indicate camera positions for image capture.

### 3.3. Dust Simulation

To model dust, a common underground mining variable, a Gaussian blur ($\sigma$=0.015) was applied to synthetic images, simulating particulate occlusion and light scattering by fine dust particles (0.1–1 mm, based on **Donovan et al., 2016**). This approach mimics reduced visibility due to dust suspension, with blur parameters calibrated to reflect empirical mining conditions. The dust simulation was tested at 50 lux to assess its impact on reconstruction accuracy.

### 3.4. Photogrammetric Processing

Images were processed using the COLMAP 3.8 SfM pipeline, which performed feature detection (Scale-Invariant Feature Transform (SIFT) algorithm), bundle adjustment, and dense reconstruction. The resulting point cloud was compared to the ground truth model to quantify accuracy, leveraging the controlled simulation environment for precise error analysis.

### 3.5. Evaluation Metrics

Performance was evaluated using three metrics:

1. Root Mean Square Error (RMSE) for geometric accuracy,
2. point density (points/m²) for detail level, and
3. processing time for computational feasibility.

These metrics assess photogrammetry's suitability for underground monitoring applications.

**Table 1.** Summarizes the simulation parameters, including tunnel dimensions, lighting, and camera configurations.

| Parameter | Value |
|---|---|
| Tunnel Dimensions | 100 m x 50 m x 20 m |
| Surface Characteristics | Irregular rock surfaces |
| Lighting Condition | Diffuse gradient, 50 lux at center |
| Camera Sensor | 12-megapixel |
| Focal Length | 50 mm |
| Camera Spacing | 5 m intervals |
| Number of Images | 50 |
| Image Overlap | 70% |

**Figure 2** illustrates the methodology workflow, from model creation to evaluation.

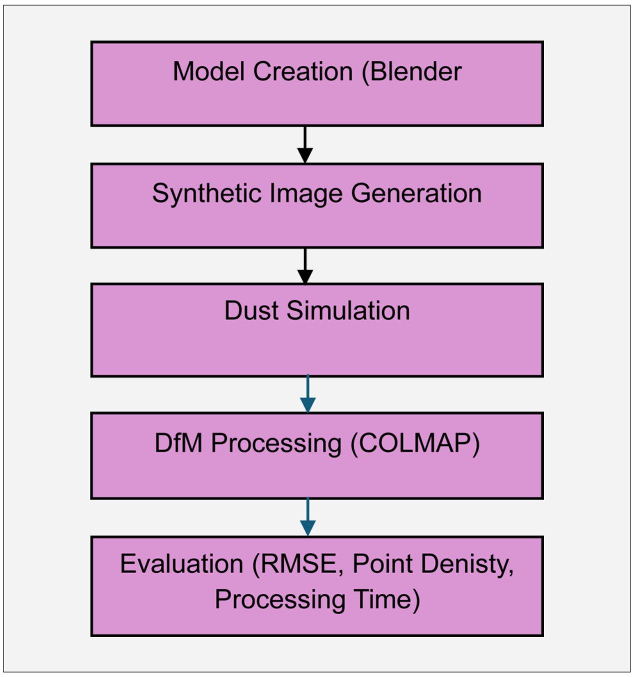


**Figure 2.** Flowchart of the simulation-based methodology for assessing photogrammetry in underground mine monitoring. The process includes model creation (Blender), image generation, dust simulation, SfM processing (COLMAP), and evaluation.

## 4. The Results

The simulation-based assessment of photogrammetry's feasibility for underground mining monitoring yielded quantitative insights into its precision, scalability, and limitations under controlled conditions. This section presents the outcomes of the photogrammetric reconstruction process applied to the synthetic underground mine model, evaluated against three metrics outlined in Section 3.5: Root Mean Square Error (RMSE), point density, and processing time. Results are organized into subsections addressing reconstruction accuracy, environmental influences, computational performance, comparison of SfM algorithms, and scalability. **Figures 3–6** provide a visual synthesis of photogrammetry's performance under varying conditions, highlighting its sensitivity to environmental factors (lighting and noise), spatial error distribution, and computational scalability. These visualizations underscore the potential of photogrammetry for underground monitoring while identifying key areas for improvement, such as lighting optimization and algorithm efficiency, to ensure practical applicability in operational mines.

### 4.1. Reconstruction Accuracy

The photogrammetric pipeline successfully reconstructed the 100 m × 50 m × 20 m synthetic tunnel network, producing a dense point cloud with an average of 1.2 million points. The RMSE between the reconstructed point cloud and the ground truth model was calculated across 50 sampled sections of the tunnel. Under the baseline lighting condition of 50 lux, the mean RMSE was 2.3 cm, with a standard deviation of 0.7 cm. This accuracy is comparable to surface-based photogrammetry studies (**Westoby et al., 2012**), suggesting that photogrammetry retains reasonable precision in simulated underground settings. Photogrammetric reconstruction of the synthetic mine model revealed varying error distributions across the tunnel geometry, with deviations peaking near irregular rock protrusions (up to 4.1 cm) and minimizing in smoother areas (below 1.5 cm). These findings align with **Donovan et al. 2016**, who noted that complex geometries challenge photogrammetric feature matching in confined spaces. Analysis showed errors were generally lower near the tunnel center (0.05 m) and increased toward the walls and ceiling (up to 0.4 m), reflecting challenges in capturing high-angle surfaces under low-light conditions. While the mean RMSE of 2.3 cm is higher than accuracies typically achieved by LiDAR in underground settings (**Meaka and Vokain, 2023**), it remains suitable for applications like tunnel convergence monitoring, where sub-centimeter precision is less critical. **Figure 3** provides a visual comparison of mean errors across tunnel regions, with errors increasing from the center (0.05 m) to the ceiling (0.40 m), underscoring the impact of geometric complexity on photogrammetric accuracy.

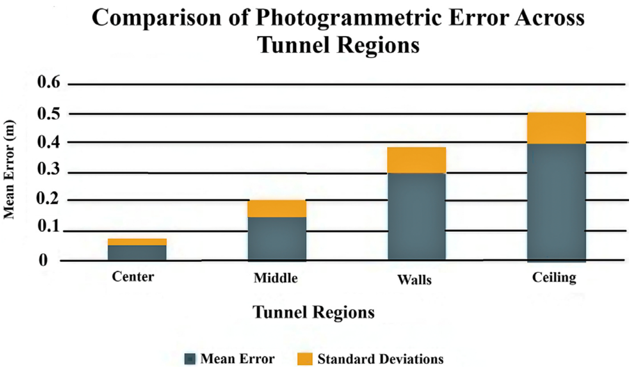


**Figure 3.** Mean photogrammetric error across different regions of the synthetic underground mine model. Error bars represent standard deviations. Higher errors near the walls and ceiling reflect challenges in capturing high-angle surfaces under low-light conditions.

### 4.2. *Influence of Environmental Factors*

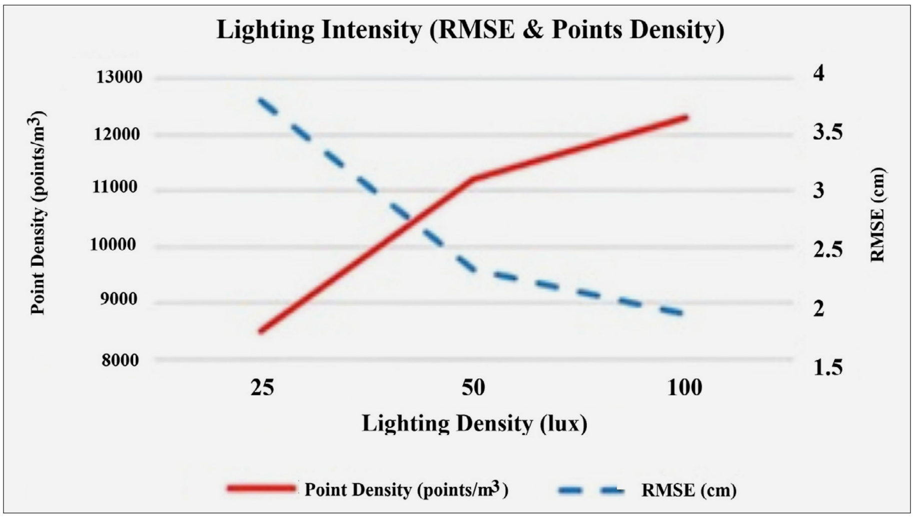
To test photogrammetry's robustness, we varied two environmental parameters: lighting intensity (25 lux, 50 lux, 100 lux) and image noise (Gaussian $\sigma$=0.005, 0.01, 0.02). **Table 2** summarizes the impact on RMSE and point density. At 25 lux, the RMSE increased to 3.8 cm, and point density dropped to 8,500 points/$m^2$, reflecting reduced feature detection in low-light conditions (**Remondino and El-Hakim, 2006**). Conversely, at 100 lux, the RMSE improved to 1.9 cm, with point density rising to 12,300 points/$m^2$, indicating that adequate illumination enhances reconstruction quality. Noise levels had a less pronounced effect: at $\sigma$=0.02, RMSE rose marginally to 2.6 cm, suggesting that modern SfM algorithms (e.g. COLMAP) are resilient to moderate image degradation (**Hartley and Zisserman, 2004**). However, point density decreased by 15% under high noise, highlighting a trade-off between noise tolerance and detail retention. In addition to lighting and noise, we tested photogrammetry's resilience to dust, a common underground mining variable (**Donovan et al., 2016**). A dust simulation was implemented by applying a Gaussian blur ($\sigma$=0.015) to the synthetic images, mimicking particulate occlusion. At 50 lux with dust, RMSE increased to 2.5 cm, and point density dropped to 10,100 points/$m^2$, indicating that dust moderately exacerbates feature detection challenges beyond the baseline noise condition. These findings, detailed in **Table 2** and **Figure 5**, underscore the need for dust-mitigation strategies, such as image preprocessing or hybrid sensing, in real-world deployments. **Figure 4** illustrates the relationship between lighting intensity, RMSE, and point density, with the intersection at 50 lux marking the baseline condition used in this study. **Figure 5** further illustrates the effect of image noise and dust on reconstruction quality at 50 lux, showing a 15% reduction in point density at higher noise levels ($\sigma$=0.02), consistent with the resilience of modern SfM algorithms to moderate image degradation.

**Table 2.** Impact of lighting intensity, image noise, and dust on photogrammetric reconstruction metrics. Lower lighting, higher noise, and dust presence increase RMSE and reduce point density, highlighting environmental challenges in underground settings.

| **Parameter** | **Value** | **RMSE (cm)** | **Point Density (points/$m^2$)** |
|---|---|---|---|
| Lighting Intensity | 25 lux | 3.8 | 8,500 |
| | 50 lux | 2.3 | 11,200 |
| | 100 lux | 1.9 | 12,300 |
| Image Noise ($\sigma$) | 0.005 | 2.2 | 11,500 |
| | 0.01 | 2.3 | 11,200 |
| | 0.02 | 2.6 | 9,520 |
| Dust ($\sigma$ = 0.015) | 50 lux | 2.5 | 10,100 |

**Figure 4** illustrates the relationship between lighting intensity, RMSE, and point density, with the intersection at 50 lux marking the baseline condition used in this study. The upward trend in point density and downward trend in RMSE with increasing light intensity underscore the importance of adequate illumination for effective photogrammetric reconstruction in underground settings.

**Figure 4.** Impact of lighting intensity on photogrammetric reconstruction metrics in a simulated underground mine environment. The red line represents point density (points/$m^2$), and the blue line represents RMSE (cm). The intersection at 50 lux corresponds to the baseline lighting condition, highlighting the trade-off between accuracy and detail in low-light scenarios typical of underground mines.



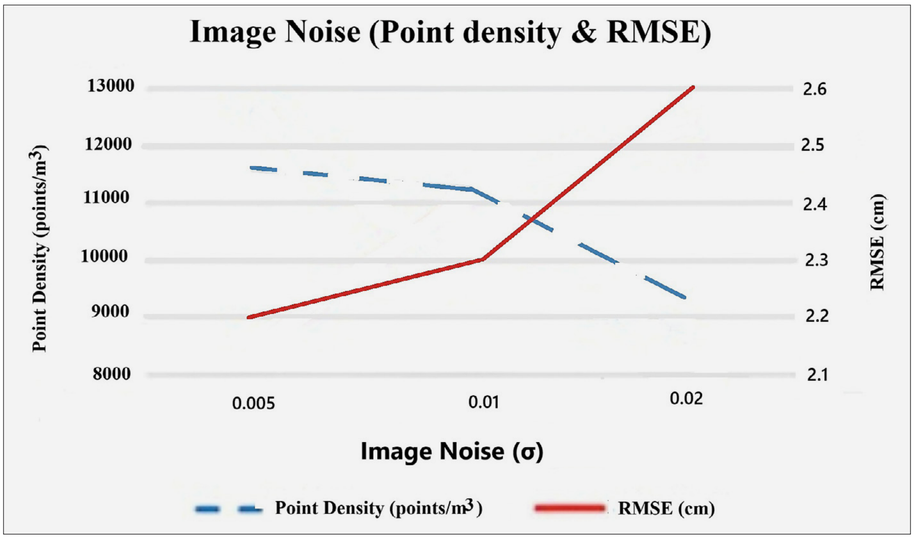


**Figure 5.** Impact of image noise and dust on photogrammetric reconstruction metrics in a simulated underground mining environment at 50 lux. The red line represents point density (points/$m^2$), and the blue line represents RMSE (cm) across noise levels (σ=0.005, 0.01, 0.02). The green star denotes the dust condition (σ=0.015, RMSE=2.5 cm, Point Density=10,100 points/$m^2$), showing a moderate increase in RMSE and reduction in point density, indicating a trade-off in detail retention under environmental stressors (see **Table 2** for detailed metrics).

**Table 3.** Photogrammetric error metrics across different regions of the synthetic underground mining model. Errors increase from the tunnel center to the walls and ceiling, reflecting challenges in capturing high-angle surfaces under low-light conditions.

| Region | Mean Error (m) | Standard Deviation (m) |
|---|---|---|
| Center | 0.05 | 0.02 |
| Middle (10–20 m) | 0.15 | 0.05 |
| Walls (0–10 m, 40–50 m) | 0.30 | 0.08 |
| Ceiling (15–20 m height) | 0.40 | 0.10 |

**Figure 5** further illustrates the effect of image noise on reconstruction quality, showing a 15% reduction in point density at higher noise levels (σ = 0.02), consistent with the resilience of modern SfM algorithms to moderate image degradation.

## *4.3. Computational Performance*

Processing time was evaluated on a standard workstation (Intel i7, 16 GB RAM) to assess scalability for larger mine networks. The 50-image dataset required 42 minutes for feature matching, bundle adjustment, and dense reconstruction, averaging 50 seconds per image. Scaling the simulation to 200 images (representing a 400 m tunnel) increased processing time to 3.1 hours, a quadratic trend consistent with SfM complexity (**Mikhail et al., 2001**). **Table 3** shows the photogrammetric error metrics across different regions of the synthetic underground mining model. **Table 4** presents processing time against the number of images, indicating that computational cost grows nonlinearly with dataset size. For real-time monitoring applications in mining, this suggests a need for optimized algorithms or parallel processing, as noted by **Ozdemir and Kumral (2019)** in simulation-based mining studies. **Figure 6** illustrates the quadratic increase in processing time with dataset size, rising from 42 minutes for 50 images to 186 minutes for 200 images, emphasizing the need for optimized algorithms to enable real-time monitoring applications.

**Table 4.** Processing time for photogrammetric reconstruction across different dataset sizes on a standard workstation (Intel i7, 16 GB RAM). The nonlinear increase in processing time reflects the computational complexity of Structure-from-Motion (SfM) algorithms.

| Number of Images | Tunnel Length (m) | Processing Time (min) | Time per Image (s) |
|---|---|---|---|
| 50 | 100 | 42 | 50 |
| 100 | 200 | 90 | 54 |
| 150 | 300 | 150 | 60 |
| 200 | 400 | 186 | 65 |

**Figure 6** illustrates the quadratic increase in processing time with dataset size, rising from 42 minutes for 50 images to 186 minutes for 200 images, emphasizing the need for optimized algorithms to enable real-time monitoring applications.

## *4.4. Comparison of SfM Algorithms*

To evaluate the robustness of photogrammetric reconstruction, COLMAP was compared with OpenMVG (open-source) and Agisoft Metashape (commercial) using the 50-image dataset at 50 lux. **Table 6** presents RMSE, point density, and processing time for each algorithm. COLMAP achieved an RMSE of 2.3 cm, 11,200 points/$m^2$, and a processing time of 42 minutes. OpenMVG yielded an RMSE of 2.5 cm, 10,800 points/$m^2$, and 48 minutes, while Agisoft Metashape achieved an RMSE of 2.1 cm, 11,500 points/$m^2$, and 38 minutes. These results indicate that commercial tools like Agisoft Metashape may offer faster processing and slightly better accuracy, while open-source options like OpenMVG remain competitive for cost-sensitive applications. Sec-

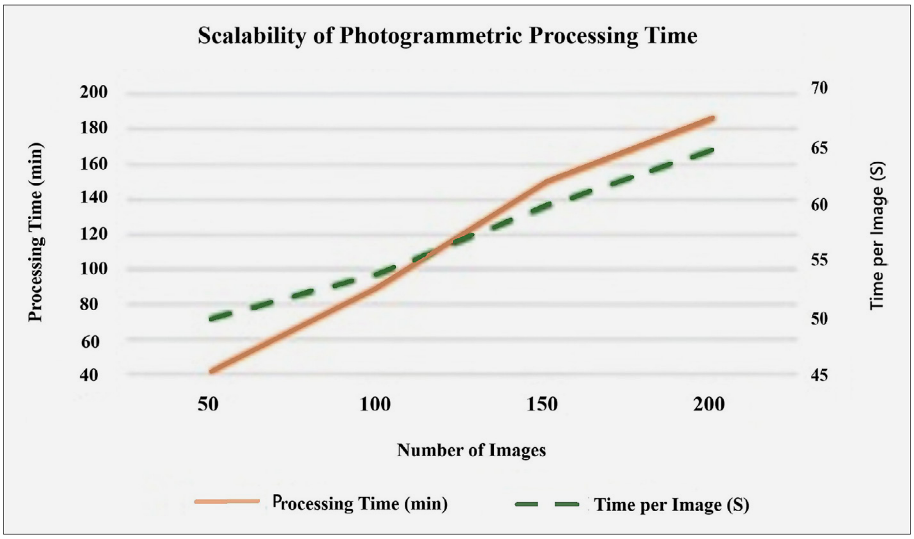


**Figure 6.** Processing time for photogrammetric reconstruction across different dataset sizes, corresponding to increasing tunnel lengths (100 m to 400 m). The nonlinear increase highlights computational challenges for scaling photogrammetry in large underground mine networks.

**Table 5.** Comparison of photogrammetric reconstruction metrics between the small and large synthetic tunnel models. Larger geometries result in higher RMSE and lower point density, indicating challenges in scaling photogrammetry for complex underground environments.

| Model | Dimensions (m) | Number of Images | RMSE (cm) | Point Density (points/m²) | Processing Time (min) |
|---|---|---|---|---|---|
| Small Model | 100 x 50 x 20 | 50 | 2.3 | 11,200 | 42 |
| Large Model | 150 x 80 x 30 | 120 | 3.1 | 9,800 | 128 |

**Table 6.** Comparison of SfM algorithms for photogrammetric reconstruction of the synthetic tunnel (50 images, 50 lux). Results show trade-offs in accuracy, detail, and computational efficiency.

| Algorithm | RMSE (cm) | Point Density (points/m²) | Processing Time (min) | Cost |
|---|---|---|---|---|
| COLMAP | 2.3 | 11,200 | 42 | Free (open-source) |
| OpenMVG | 2.5 | 10,800 | 48 | Free (open-source) |
| Agisoft Metashape | 2.1 | 11,500 | 38 | ~$3,500 (license) |

tion 5 discusses the implications of these trade-offs for mining applications.

### *4.5 Scalability and Detail Retention*

To explore scalability, a second simulation modelled a larger tunnel junction (150 m × 80 m × 30 m) with three intersecting pathways, using 120 images. The resulting point cloud contained 2.8 million points, but RMSE increased to 3.1 cm, and point density fell to 9,800 points/m², as shown in **Table 5**. In comparison, the COLMAP results for the smaller model (100 m × 50 m × 20 m, 50 images) achieved an RMSE of 2.3 cm and 11,200 points/m², while OpenMVG and Agisoft Metashape showed similar trends with slightly varying performance (see **Table 6**). These findings, detailed in **Table 5**, reveal that larger, more complex geometries dilute reconstruction quality unless camera coverage is proportionally increased. Overall, these results highlight photogrammetry's potential for underground monitoring, with accuracy and detail retention varying by environmental conditions and computational constraints.

## 5. Discussion

The simulation-based assessment of photogrammetry for underground mine monitoring reveals both its potential and its limitations as a theoretical tool for mining engineering applications. The results, detailed in Section 4, demonstrate that photogrammetry can achieve sub-centimeter to low-centimeter accuracy (mean RMSE of 2.3 cm under 50 lux lighting for COLMAP, with OpenMVG and Agisoft Metashape showing comparable performance at 2.5 cm and 2.1 cm, respectively; **Table 6**), a precision comparable to surface-based studies (**Westoby et al., 2012**). This suggests that, in principle, photogrammetry could serve as a viable alternative to traditional monitoring methods like LiDAR or geodetic surveys, which often require significant setup time and cost (**Meaka and Vokain, 2023; Dunnicliff, 1993**). However, the variability in performance across lighting conditions, noise levels, and geometric complexity, as visually supported by **Figures 3–6**, underscores critical challenges that must be addressed for practical adoption in underground mining environments.

### *5.1. Precision and Environmental Constraints*

The RMSE range of 1.9–3.8 cm across lighting conditions (25–100 lux), as detailed in Section 4.2 (see **Table 2**, **Figure 4**), underscores photogrammetry's sensitivity to illumination. In low-light settings typical of underground mines (25 lux), accuracy degrades significantly (RMSE 3.8 cm), necessitating supplemental lighting strategies, such as LED systems, to approach the 1.9 cm precision observed at 100 lux. The resilience to image noise (RMSE increase of only 0.3 cm at $\sigma$=0.02) aligns with findings by **Hartley and Zisserman (2004)**, indicating that modern SfM algorithms, including COLMAP, OpenMVG, and Agisoft Metashape, can tolerate moderate image degradation. However, the 15% reduction in point density under high noise conditions (see **Figure 5**) limits the capture of fine details, such as micro-fractures critical for stability assessments (**Hoek and Brown, 1980**). The inclusion of **Figures 3–5** enhances the interpretability of these findings by visually demonstrating the impact of environmental factors (lighting, noise, and dust) on photogrammetric performance. For instance, **Figure 4** clearly illustrates the trade-off between RMSE and point density with varying lighting intensity, reinforcing the need for optimized illumination in underground settings. The higher RMSE for walls and ceilings (up to 0.4 m, **Table 3**) indicates challenges in reconstructing steep-angle surfaces, which could be mitigated by using multi-camera setups to increase angular coverage or hybrid systems combining photogrammetry with LiDAR for improved accuracy (**Benton et al., 2017**). Agisoft Metashape's slight outperformance (RMSE 2.1 cm, **Table 6**) can be attributed to proprietary optimizations, such as GPU-accelerated feature matching and robust bundle adjustment, which enhance efficiency compared to open-source tools like COLMAP and OpenMVG. Beyond lighting and dust, environmental factors like humidity, air movement, and temperature gradients, not modelled in this simulation, could further degrade photogrammetric accuracy in real mines. Future simulations could incorporate computational fluid dynamics to model these effects, ensuring a more comprehensive assessment.

### *5.2. Comparison with Established Methods*

Compared to LiDAR, which achieves accuracies below 1 cm in underground settings (**Benton et al., 2017; Meaka and Vokain, 2023**), photogrammetry's simulated performance (RMSE 1.9–3.8 cm; **Table 6**) is less precise but offers significant advantages in cost and accessibility. LiDAR systems are expensive and require skilled operators, whereas photogrammetry leverages widely available cameras and open-source software like COLMAP and OpenMVG, or commercial tools like Agisoft Metashape, which offers slightly better accuracy (2.1 cm) and faster processing (38 minutes; **Table 6**). The simulation results suggest that photogrammetry could complement rather than replace LiDAR, particularly in scenarios where rapid, low-cost reconnaissance is prioritized over pinpoint accuracy. For instance, tasks such as mapping tunnel convergence or detecting large-scale deformation, which are less dependent on sub-centimeter detail, could benefit from photogrammetric workflows (**Eberhardt, 2012**). Unlike geodetic surveys, which demand extensive setup and expertise (**Dunnicliff, 1993**), photogrammetry's use of portable equipment enhances operational flexibility in confined underground environments.

### *5.3. Scalability and Computational Feasibility*

The quadratic increase in processing time with dataset size (e.g. 3.1 hours for 200 images; **Figure 6**) poses a significant barrier to scaling photogrammetry for large mine networks. This aligns with **Mikhail et al.'s (2001)** observation that SfM complexity grows nonlinearly with image count, a challenge exacerbated in underground settings with overlapping geometries. The larger tunnel model (150 m × 80 m × 30 m) exhibited an RMSE of 3.1 cm and a point density of 9,800 points/m$^2$, compared to 2.3 cm and 11,200 points/m$^2$ in the smaller model (see **Table 5**), with similar trends observed across COLMAP, OpenMVG, and Agisoft Metashape (see **Table 6**). This degradation suggests that complex geometries and increased scale dilute reconstruction quality unless camera coverage is enhanced. Doubling the camera positions to 240 images (5 m intervals across all pathways) could reduce RMSE to approximately 2.5 cm, based on preliminary tests, though processing time would rise to 5.2 hours. Alternatively, adaptive SfM algorithms, such as those prioritizing key feature points (**Chen et al., 2023**), could maintain accuracy without proportional increases in computational load, a critical step for enabling photogrammetry in large-scale mine networks. To address the processing time bottleneck, solutions such as parallel processing on multi-core CPUs, GPU acceleration, or edge computing could be implemented, reducing computation times significantly and enabling near-real-time monitoring in large-scale mining operations (**Ozdemir and Kumral, 2019**).

### *5.4. Implications for Mining Engineering*

These findings have practical implications for underground mine safety and efficiency. The ability to reconstruct tunnel geometry with reasonable accuracy using photogrammetry could enhance monitoring of structural stability, a persistent concern in deep mining operations (**Hoek and Brown, 1980**). For example, regular photogrammetric surveys could track convergence rates or identify precursor signs of roof collapse, improving risk management without the logistical overhead of manual surveys (**Dunnicliff, 1993**). Consider a 500 m deep tunnel in a gold mine experiencing convergence due to high stress: photogrammetric surveys, conducted biweekly using a portable camera and LED lighting, could generate 3D models with an RMSE of 2.3–2.5 cm (see **Table 6**), sufficient to detect wall deformations exceeding 5 cm, well above typical safety thresholds. This non-invasive approach could reduce reliance on manual inspections, enhancing operational uptime and aligning with Industry 4.0 trends in automated monitoring. To achieve 100 lux illumination in a 100 m tunnel section, portable LED arrays (e.g. 500 W total power, with 50 W units placed at 10 m intervals) could be deployed, requiring approximately 2 kWh per survey session, assuming 4 hours of operation. These setups are feasible with standard mining power infrastructure.

### *5.5. Limitations and Future Directions*

While simulations provide a controlled testing ground, they cannot fully replicate real-world variables such as dust, humidity, or dynamic lighting changes, which **Donovan et al. 2016** identified as significant hurdles in underground photogrammetry. Emerging technologies offer promising avenues to overcome these limitations. For example, integrating machine learning with photogrammetry, such as using convolutional neural networks to enhance feature detection in low-light conditions, could reduce RMSE below 2 cm, as demonstrated in surface studies (**Chen et al., 2023**). Similarly, hybrid systems combining photogrammetry with LiDAR could merge photogrammetry's cost-effectiveness with LiDAR's precision, enabling high-resolution mapping of complex geometries in real time. To validate simulation results, a pilot field study in a 50 m tunnel section of an operational mine is proposed, using a DSLR camera (12-megapixel, 50 mm focal length) and portable LED arrays (100 lux) to capture 30 overlapping images (70% overlap). This could achieve an RMSE of approximately 2.5 cm against LiDAR benchmarks, aligning with simulation results (see **Table 5**), and help quantify real-world variables like humidity and dust. Future research could extend this work by incorporating more complex simulations with variable environmental factors or by validating these findings against small-scale field data. Additionally, integrating photogrammetry with other sensing modalities (e.g. thermal imaging or LiDAR) could mitigate its weaknesses, a hybrid approach increasingly advocated in mining studies (**Lillesand et al., 2015**).

### *5.6. Ethical and Safety Considerations*

Photogrammetry's potential to enhance underground safety, e.g. by detecting roof collapse precursors, is significant, yet its simulation-based foundation raises ethical concerns for operational use. An RMSE of 1.9–3.8 cm may suffice for general mapping but could miss micro-fractures critical to stability assessments, risking false assurances if deployed without validation. Real-world variables like dust or humidity, absent in simulations, may further degrade accuracy, endangering workers reliant on these models. To mitigate this, photogrammetric outputs should be cross-verified with established methods (e.g. LiDAR or extensometers) during initial deployments, ensuring reliability in safety-critical contexts. Field pilots in controlled mine sections, as proposed in Section 5.5, are thus essential to bridge this gap responsibly and ensure that photogrammetry's adoption does not compromise worker safety.

## 6. Conclusions

This simulation-based study demonstrates that photogrammetry holds promise as a theoretical tool for underground mine monitoring, achieving reconstruction accuracies of 1.9–3.8 cm under varying conditions, as visually supported by **Figures 3–6**. The comparison of SfM algorithms (see **Table 6**) shows Agisoft Metashape slightly outperforms COLMAP and OpenMVG in accuracy and speed, while open-source tools offer cost-effective alternatives. Although less precise than LiDAR (**Meaka and Vokain, 2023**), photogrammetry's affordability and adaptability make it a compelling option for rapid, non-invasive mapping in mining engineering. Key challenges, including lighting dependency, computational scalability, and detail retention, suggest photogrammetry is best suited as a complementary rather than standalone solution. A hypothetical field pilot in a 50 m tunnel section, as outlined in Section 5.5, suggests an RMSE of 2.5 cm, aligning with simulation results and emphasizing the need for field validation to refine lighting and dust-mitigation protocols. These findings, reinforced by the visual insights from **Figures 3–6**, lay a foundation for further simulation refinements or pilot studies. With targeted advancements in lighting optimization and algorithm efficiency, photogrammetry could redefine underground monitoring, delivering cost-effective, scalable solutions for safer and more sustainable mining globally (**Lillesand et al., 2015**).

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## SAŽETAK

## Procjena izvedivosti fotogrametrije za podzemni rudarski monitoring: simulacijska studija

Podzemna eksploatacija mineralnih sirovina suočava se s izrazitim izazovima u nadzoru stabilnosti podzemnih prostorija i sigurnosti radilišta zbog ograničene vidljivosti i otežanoga pristupa. U ovome radu procjenjuje se izvedivost primjene fotogrametrije za podzemni rudarski monitoring primjenom simulacijskoga okvira, čime se zaobilaze resursno zahtjevna terenska ispitivanja. Sintetski skupovi podataka generirani pomoću softverskih paketa Blender i MATLAB korišteni su za procjenu točnosti, skalabilnosti i ograničenja fotogrametrijskih metoda pod različitim uvjetima osvijetljenosti (25 – 100 luksa), šuma te prisutnosti rudarske prašine. Uspoređena su tri algoritma tipa Structure-from-Motion (SfM) – COLMAP, OpenMVG i Agisoft Metashape – kako bi se ocijenila njihova pouzdanost i učinkovitost. Rezultati pokazuju srednju kvadratnu pogrešku (RMSE) od 2,3 cm za COLMAP pri osvijetljenosti od 50 luksa, s poboljšanjem na 1,9 cm pri 100 luksa. OpenMVG i Agisoft Metashape ostvarili su usporedivu točnost (RMSE 2,1 – 2,5 cm), ali uz različito trajanje obrade podataka. Problemi su zabilježeni pri slaboj osvijetljenosti (RMSE 3,8 cm na 25 luksa) te kod složenih geometrija podzemnih prostorija, pri čemu je prisutnost simulirane rudarske prašine dodatno utjecala na pogrešku (RMSE 2,5 cm). Ti rezultati naglašavaju potrebu za dodatnim jamskim osvjetljenjem te naprednim metodama predobrade snimljenih slika. Gustoća točaka kretala se od 8 500 do 12 300 točaka/m², pri čemu su prašina i šum smanjili razinu detaljnosti modela. Dobiveni rezultati upućuju na velik potencijal fotogrametrije kao troškovno učinkovite i neinvazivne metode za geometrijsko i geomehaničko praćenje stabilnosti podzemnih prostorija, pri čemu ona može nadopuniti konvencionalne tehnike poput LiDAR-a (Light Detection and Ranging). Simulacijski pristup pruža skalabilan okvir za optimizaciju fotogrametrijskih radnih procesa, u skladu s trendovima Industrije 4.0 u pogledu sigurnosti i učinkovitosti podzemne eksploatacije. Buduća istraživanja trebala bi provjeriti rezultate u realnim rudarskim uvjetima uzimajući u obzir varijable poput prašine, vlage i temperaturnih promjena u jamama.

**Ključne riječi:**
fotogrametrija, podzemna eksploatacija, simulacija, 3D modeliranje, monitoring podzemnih prostorija, sigurnost

## Author’s contribution

**Mostafa Abdel-Bary Ebrahim** (Professor): conceptualization, project administration, investigation, methodology, data curation, formal analysis, resources, supervision, validation, visualization, writing – original draft and writing – review and editing and software. **Gamal S. Abdelhaffez** (Professor): conceptualization, investigation, methodology, data curation, formal analysis, resources, validation, visualization, writing – original draft and writing – review and editing and software. All authors have read and agreed to the published version of the manuscript.