Detection of distress in rural road pavements: an analysis of UAV altitude variations

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Abstract

Ensuring the safety of road networks is a fundamental priority in both urban and rural contexts. The degradation of asphalt surfaces, an inevitable process, is driven by several factors, including the fourth power of axle loads imposed by vehicles, the use of materials that do not always meet high-quality standards, the growing volume of traffic, persistent congestion, and the effects of climate change. Initial damage often appears in the form of longitudinal, transverse, alligator, or block cracks. If not addressed promptly, these defects can progress into potholes, significantly increasing road hazards and repair costs. For municipal authorities, the economic burden of repairing potholes far exceeds that of addressing cracks at an earlier stage, highlighting the critical importance of timely maintenance interventions. Continuous monitoring of pavement conditions is essential to mitigate these risks. However, the frequency of assessments required for effective monitoring presents a challenge when traditional techniques are employed, as they are often associated with high costs and resource demands. Drone-based photogrammetry offers a cost-effective alternative, enabling efficient and accurate evaluations of pavement conditions. Despite its advantages, a significant gap exists in the parametric data linking measurement accuracy to flight altitude, limiting its optimisation for practical applications. This study investigates the relationship between flight altitude and measurement precision, analysing root mean square (RMS) values at altitudes of 5m, 10m, 15m, 20m, and 25m. The findings aim to provide a clearer understanding of the trade-offs between altitude and accuracy, contributing to the refinement of drone-based methodologies for pavement monitoring.

1. Introduction

This research highlights the critical role of road safety in both urban and rural areas, emphasizing the susceptibility of asphalt surfaces to deterioration caused by heavy vehicle loads, substandard materials, increasing traffic volumes, and the growing impacts of climate change. Four primary forms of early-stage road damage are identified: longitudinal cracks, transverse cracks, alligator cracks, and block cracks. If these defects are not promptly addressed, they can progress into more severe issues, such as potholes, which significantly elevate both safety risks and repair costs. From an economic perspective, the burden of pothole repairs often far exceeds that of addressing cracks during their initial stages, underscoring the necessity for systematic pavement monitoring. Traditional monitoring methods, while effective, are associated with considerable costs, driving interest in drone-based photogrammetric techniques as a more economical alternative. However, a notable gap exists in parametric data linking the accuracy of these methods to flight altitude, highlighting the need for targeted research to optimize their application in road condition assessments. A key parameter in drone-based evaluations is the Ground Sampling Distance (GSD), which determines the resolution of captured images. Smaller GSD values correspond to higher image detail, while larger GSD values result in diminished resolution (Table 1). The GSD is influenced by three critical factors: altitude, camera specifications, and zoom capabilities.

- Altitude: The relationship between GSD and altitude is directly proportional. As altitude increases, the GSD value rises, leading to reduced image resolution. Conversely, lower altitudes yield smaller GSD values, enhancing image detail.
- Camera Specifications: The impact of altitude on GSD is moderated by the drone camera's specifications, particularly sensor size and focal length. Drones operating at the same altitude may produce different GSD values due to variations in camera configurations.
- Zoom Capabilities: Zoom-enabled cameras can partially counteract the direct correlation between altitude and GSD. For example, a drone flying at a higher altitude but equipped with a zoom lens may achieve a GSD similar to that of a drone flying at a lower altitude without zoom capabilities.

Understanding the interplay between these factors is essential, particularly regarding their influence on the final accuracy of road safety metrics. This study underscores the importance of further investigation into the relationship between flight altitude and GSD to refine drone-based methodologies, enhancing their reliability and cost-effectiveness for pavement monitoring and maintenance.

Altitude (m)	GSD (cm/pixel)	Image Detail Level
5	1.0	High
10	2.3	Medium-High
20	4.6	Medium
40	9.0	Low

Table 1. GDS values for different heights

Operating at lower flight altitudes enables finer Ground Sampling Distance (GSD), resulting in enhanced image detail. However, the risks associated with flying in close proximity to obstacles often outweigh these advantages, particularly in complex environments. In such situations, surveyors may choose slightly higher altitudes to achieve a balance between image resolution and drone safety. High-resolution imagery, associated with low GSD values, also demands substantial storage capacity and processing power, requiring surveyors to carefully evaluate their data handling capabilities when determining the optimal GSD and corresponding flight altitude.

For road pavement monitoring, where metric accuracy requirements are typically on the order of millimetres, flight altitude must be meticulously planned at the outset. This parameter plays a critical role in ensuring that the collected data meets the precision standards necessary for assessing pavement degradation effectively.

In drone surveying, decisions regarding flight altitude have significant implications for both image quality and operational efficiency. Reducing altitude improves GSD, delivering superior image resolution. However, this approach introduces operational challenges, including increased flight durations and heightened data processing demands. Surveyors must navigate these trade-offs to optimise image quality while maintaining practical and efficient survey workflows (Table 2).

Aspect	Lower altitude flight	Challenges
Ground Sampling Distance (GSD)	Enhanced (Finer)	Larger volume of images
Flight Times	Longer due to slower speeds and reduced coverage area	Multiple battery swaps or flight missions
Image Volume	Higher	Increased storage and data management demands
Processing Times	Extended	Higher computational power and longer time requirements
Operational Costs	Potentially higher	Additional batteries, wear and tear, labor, and processing costs

Table 2. Trade-offs and challenges associated with lower altitude UAV flights for pavement monitoring (Inzerillo et al., 2022; Outay et al., 2020).

At lower flight altitudes, the area captured by each image is significantly reduced. To cover the same survey area, the drone must capture a greater number of images, often requiring a slower operational speed, which extends flight durations. This can necessitate multiple battery replacements or even additional flight missions, increasing the overall survey time.

Capturing a higher volume of images at reduced altitudes also generates substantial data, presenting logistical challenges in terms of transfer, storage, and organization. Advanced storage solutions and meticulous data management practices are essential to handle these demands effectively. Additionally, photogrammetry software, tasked with integrating drone-captured images into coherent maps or three-dimensional models, encounters heightened computational demands due to the increased data volume. The processing of high-resolution images requires significantly more computational power and time, potentially causing project delays if the available infrastructure is not equipped to handle the workload efficiently.

Prolonged flight durations and associated data challenges contribute to increased operational costs. These may stem from the need for additional batteries, increased wear and tear on drones, or extended labour hours. Moreover, the requirement for enhanced storage and processing capabilities often necessitates investments in upgraded hardware and software, further impacting project budgets.

This study presents the findings of a flight experiment conducted at varying altitudes, offering accuracy metrics that correlate initial flight parameters with consistent levels of road surface degradation. These results aim to support researchers and professionals in optimizing flight strategies for effective and efficient road condition monitoring.

2. State of the art

Recent advancements in 3D imaging technologies have significantly enhanced the monitoring and analysis of road pavement conditions, offering cost-effective and precise solutions through the integration of photogrammetry and Unmanned Aerial Vehicles (UAVs)(Leonardi et al., 2019; Roberts et al., 2020; Zhang and Elaksher, 2010).

Structure from Motion (SfM) has proven to be a transformative photogrammetric method, enabling the reconstruction of 3D models from overlapping 2D images. By automating image alignment and parameter refinement through advanced algorithms, SfM streamlines the reconstruction process(Eltner and Sofia, 2020). Data collection typically involves ground-based cameras or UAVs capturing images with approximately 70% overlap between frames. These images are processed using specialised software, such as Agisoft PhotoScan, to generate dense 3D point clouds. Validation studies against laser scanning models confirm that SfM effectively replicates pavement distresses, such as cracks and rutting, providing a cost-efficient alternative to traditional laser-based methods(Inzerillo et al., 2018).

UAVs have further revolutionised pavement monitoring by enabling the rapid and large-scale acquisition of high-resolution imagery over extensive road networks. These systems overcome the logistical constraints of ground-based methods and allow for efficient data collection (Peddinti et al., 2023). When integrated with SfM workflows, UAVs facilitate the creation of detailed 3D models with minimal human intervention. However, UAV operations are not without limitations. Environmental factors, including weather conditions and flight vibrations, alongside regulatory restrictions, may limit their deployment in certain areas (Zakeri et al., 2017; Zeybek and Biçici, 2020). Despite these challenges, UAV-based approaches have demonstrated exceptional effectiveness in surveying large road networks, far exceeding the capabilities of earlier point-specific methods.

Super-resolution (SR) imaging has emerged as an indispensable tool for enhancing the accuracy of 3D models derived from low-resolution inputs. By interpolating sub-pixel information, SR algorithms reconstruct high-resolution images, significantly improving the fidelity of 3D reconstructions(Wang et al., 2022). These techniques are particularly effective for identifying surface anomalies, such as cracks. Recent studies highlight the potential of SR methods, including machine learning-based algorithms like SRCNN, to reduce noise, enhance texture detail, and improve model accuracy. By addressing limitations associated with high-altitude UAV captures or challenging imaging conditions, SR imaging enhances the reliability and precision of pavement monitoring workflows (Inzerillo et al., 2022). The combined methodology reduces costs, improves accuracy, and supports continuous pavement monitoring. Furthermore, it provides transportation authorities with actionable insights to optimise maintenance strategies and resource allocation.

While transformative, these 3D imaging technologies face several challenges. The trade-off between cost and accuracy remains a critical consideration. Although SfM and UAVs offer substantial cost advantages over laser-based systems, environmental factors can impact their accuracy. Additionally, the dense datasets produced by these workflows demand significant computational resources and advanced software for processing (Inzerillo et al., 2018). Another limitation lies in the absence of standardised protocols and open-access datasets to benchmark these methodologies. Addressing these challenges requires efforts to enhance algorithm robustness, expand publicly accessible datasets, and develop real-time processing capabilities to ensure scalability and broader adoption.

3. Methodology

Prior to initiating a drone survey, it is essential to conduct a comprehensive assessment of the project’s specific requirements. In cases where precision is critical, the extended flight durations and increased costs associated with lower altitudes may be justified. Conversely, for broader applications, such as large-scale agricultural or land evaluations, the efficiency of operating at higher altitudes often takes precedence.

Recent advancements in drone and camera technology have addressed several challenges inherent to low-altitude surveys. Features such as extended battery life, faster data transfer rates, and advanced onboard processing capabilities have significantly improved the feasibility of such operations. Additionally, precise flight planning is crucial. By optimizing flight paths to ensure sufficient image overlap and redundant coverage, surveyors can minimize logistical challenges and streamline data acquisition(Outay et al., 2020).

Altitude, while a critical factor, is not the only parameter requiring careful calibration. Speed must also be adjusted appropriately, particularly at lower altitudes, to mitigate motion blur, which can compromise image quality. Operating at reduced altitudes places the drone in closer proximity to the ground or target surface, magnifying the effects of even minor speed variations. This sensitivity, combined with the finer Ground Sampling Distance (GSD) achieved at lower altitudes, makes motion blur more pronounced and detrimental to the overall quality of the imagery (Booth and Cox, 2006). Motion blur occurs when significant movement of the drone or camera takes place during the exposure time of an image. Excessive speeds relative to altitude result in blurred or smeared images due to the rapid displacement of the drone over the ground. To address this, flight speed must be calibrated in alignment with the selected altitude. Modern photogrammetry tools, such as DroneDeploy® and Pix4D®, often include automated settings to adjust speed relative to altitude, reducing the risk of motion blur. Additionally, stabilization technologies, such as GPS and gimbals, help counteract minor vibrations and positional shifts, further enhancing image clarity. Complementary adjustments, such as employing faster shutter speeds, can also diminish motion blur but may necessitate increased lighting or modifications to ISO and aperture settings.

Continuous monitoring of captured imagery during the survey is imperative. If motion blur is detected, immediate corrective actions, such as reducing the drone’s speed, increasing altitude, or refining camera setting, should be implemented to ensure data integrity.

In this study, focused on road pavement monitoring with a required metric accuracy of one millimetre, a flight altitude of up to 25 meters was established, with subsequent flights conducted at intervals down to a minimum altitude of 5 meters. An initial proposal to employ a parametric adjustment mechanism for camera calibration proportional to flight altitude was evaluated but ultimately deemed unfeasible. Preliminary results, even at the highest camera quality settings and an altitude of 15 meters, achieved a metric accuracy of only one centimeter, insufficient for the precision required in road pavement assessments.

To meet the target root mean square (RMS) accuracy of one millimetre, the camera was calibrated at maximum resolution at the minimum altitude. Subsequent flights at varied altitudes were conducted while maintaining constant camera parameters, ensuring the precision necessary for effective pavement condition assessments.

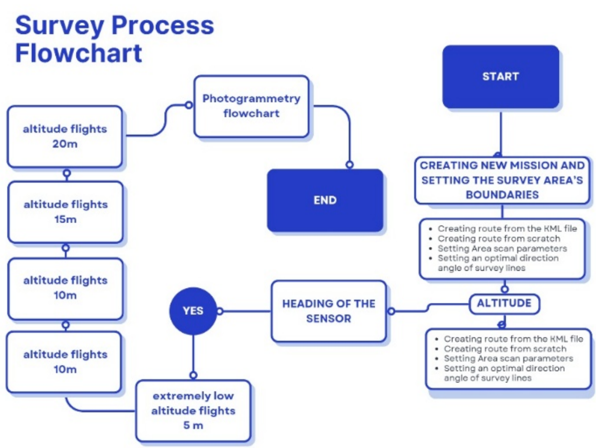


Figure 1. Survey process.

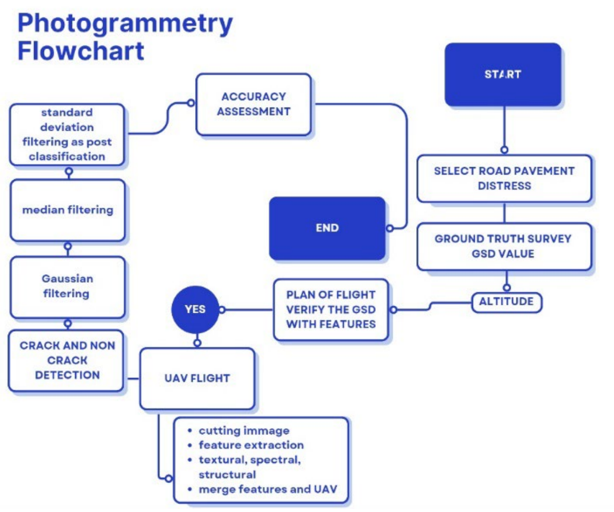


Figure2. Photogrammetric process.

The quality of pavement surface images is influenced by numerous factors, including variations in brightness (such as bright sunlight or overcast conditions), the presence of random grainy textures, inconsistent lighting, unstable shadows, asphalt markings, watermarks, and other related disturbances. These variables pose significant challenges for the identification and detection of cracks using image processing techniques. To mitigate their impact, post-classification smoothing is employed to enhance the accuracy and reliability of image analysis. In this investigation, Gaussian filtering, median filtering, and standard deviation filtering are applied as post-classification smoothing techniques to improve the quality of pavement surface images (Equation 1). These methods aim to reduce the adverse effects of the aforementioned variables, thereby enhancing the overall effectiveness of the image processing workflow.

$$G_{(n,m)} = \frac{1}{2\pi\sigma^2} e^{-\frac{n^2+m^2}{2\sigma^2}} \quad (1)$$

where σ is the Gaussian filter standard deviation, n and m are pixel indexes, and G(n,m) is the mask element value.

4. Case Study

The case study examined a section of the SP44bis, an inter-municipal road in the province of Palermo, connecting the towns of Bisacquino and Contessa Entellina. The road features a 7-metre-wide carriageway designed for two-way traffic (Figure 3).

Figure 3. Survey location (Source: Google Hearts).

After identifying the survey area of interest, the flights were planned to use the low-cost Litchi® application, specifically designed for Mavik DJI® drones. A consistent planimetric flight path was maintained for all programmed missions, with flight altitude being the only variable adjusted across 5, 10, 15, 20, and 25 metres. Additional flight parameters were configured to ensure adequate image overlap at the lowest altitude (Table 3).

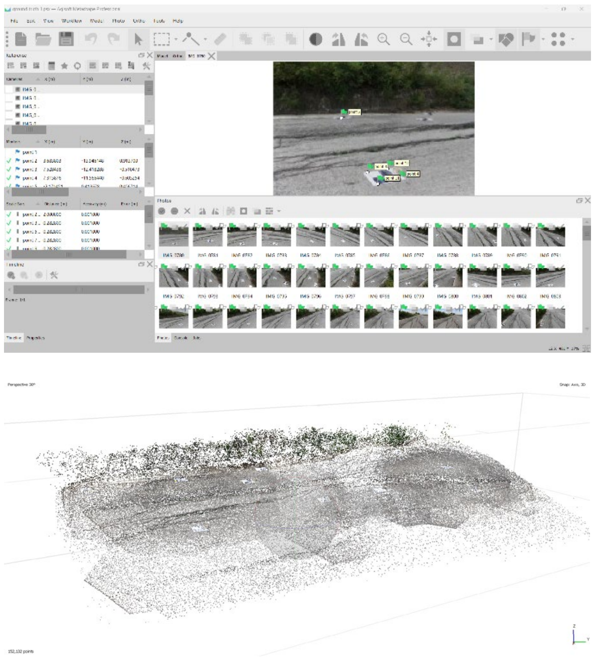
The selection of photogrammetric parameters was preceded by preliminary test flights aimed at calibrating and optimising these configurations. A single combination of parameters was applied across all altitudes to ensure superior results, leveraging the high degree of overlap between the captured images.

Heading Mode	Automatic
Path Mode	Curved Turns
Cruising Speed	0.3 m/s
Photo Capture Interval	0.5 second
Default Curve Size	75%

Table 3. UAV flight parameters setting

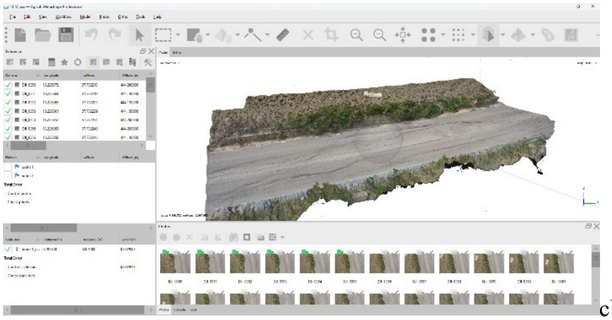
Concerning the photogrammetric survey, a DJI Mavic PRO 2 drone equipped with a Hasselblad L1D-20c camera was deployed, while a Canon EOS 1000D camera fitted with an EF-S 18-55mm f/3.5-5.6 IS II lens was used for ground-based measurements, serving as a comparative reference. During the preparatory phase, markers were strategically placed on the carriageway at identified areas of degradation to facilitate image alignment and ensure precise scaling of the surveys.

Upon completing the photographic acquisition, the Structure-from-Motion (SfM) technique was employed using Agisoft Metashape® software. This approach enabled the three-dimensional reconstruction of dense point clouds, encompassing both the aerial photogrammetric surveys conducted at varying altitudes and the ground-based reference survey (Ground Truth). In Figure 4 the dense cloud reconstruction is shown.



a)

b)



c)

Figure 4. Dense point cloud reconstruction in Agisoft Metashape® software.

The comparison and analysis of the generated point clouds were performed using the open-source software CloudCompare®. Point clouds captured at varying altitudes were aligned with the reference cloud to ensure precise overlap. For the purpose of this evaluation, the analysis focused on a specific section of the identified road pavement distress, concentrating on an area of longitudinal cracking covering a surface of 7681.65 cm². (Figure 5).

Figure 5. Longitudinal crack selected for the analysis.

To assess variations in survey precision, the distances between points in the three-dimensional models generated through aerial photogrammetric surveys conducted at different altitudes were compared with those in the three-dimensional model obtained from ground-based photogrammetric surveys.

Distance calculations were performed using CloudCompare software, employing the local 2D1/2 Triangulation model (Figure 6). This method allows for a more accurate approximation of the true distances between points in a data cloud and those in a reference cloud, which is locally modelled as a triangulated surface. In the context of this approach a detailed and precise analysis of geometric discrepancies between the datasets was ensured.

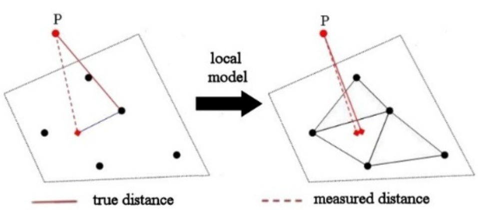


Figure 6. Schematic representation of the local 2D1/2 Triangulation model.

5. Results and discussion

The 3D models from the different UAV flights were compared with the ground truth 3D model using CloudCompare software (Figure 7). In particular, the C2C distance computation algorithm allowed the implementation of the Hausdorff distance between two subsets of the same metric space, which is defined (Ryu and Kamata, 2021):

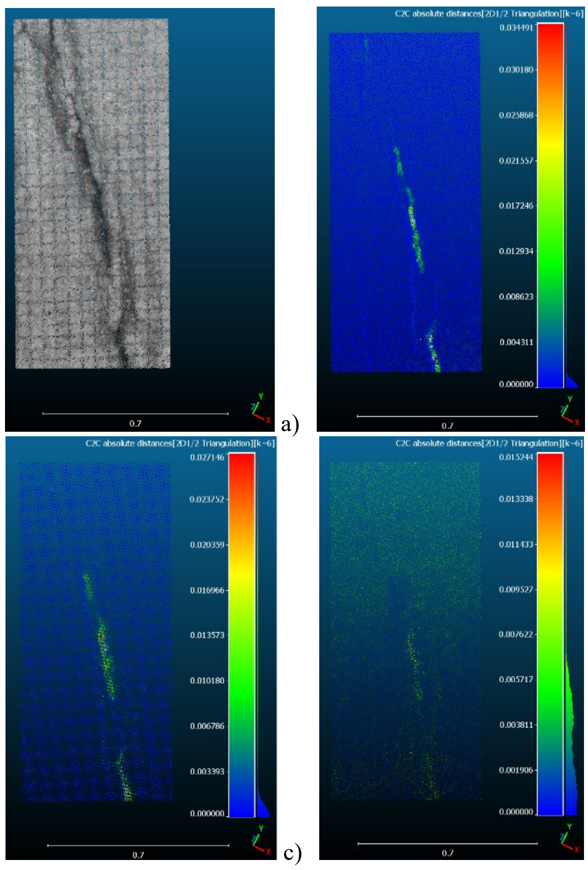
$$H(A,B) = \max\,[h(A,B), h(B,A)] \quad (2)$$

$$h(A,B) = maxmin||a - b|| \quad (3)$$

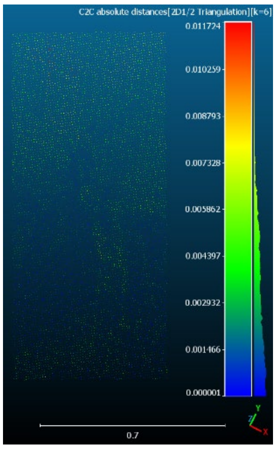
where h(A,B) is the calculated Hausdorff distance from the subset A to the subset B.

The graphical output of the Hausdorff distances, as output of clouds from UAV surveys and the ground truth model comparison, and their Root Mean Square values, underlined the loss of definition as the detection altitude increased

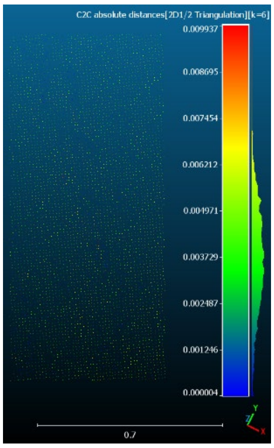
Using the specific features of the software, comparison point clouds were generated for each flight altitude, providing information on the distances between the clouds captured at various altitudes and the ground truth (Figure 7).



a) b) c) d)



e)



f)

Figure 7. Analysis of absolute distances between the Ground truth (a) and surveys conducted at different altitudes: 5 m (b); 10 m (c); 15 m (d); 20 m (e); 25 m (f).

The analysis of the collected data demonstrates a clear inverse relationship between flight altitude and both the metric accuracy and spatial density of the generated point clouds. Root Mean Square (RMS) values calculated for point clouds at different altitudes reveal a progressive loss of accuracy with increasing altitude. Specifically, RMS values rise from 0.0016 mm at 5 m to 0.0039 mm at 25 m, reflecting a 143% increase in error (Figure 8, Table 4). This trend is non-linear, with an accelerated rate of error growth at higher altitudes, highlighting the compounded effects of reduced image detail and the challenges in maintaining metric precision.

Altitude (m)	RMS	Number of points	Points for cm^2
5	0,00163149	112280	14,62
10	0,00197091	38964	5,07
15	0,00334083	18955	2,47
20	0,00349978	9269	1,21
25	0,00396369	5256	0,68

Table 4. RMS values and point counts of dense clouds at different altitudes.

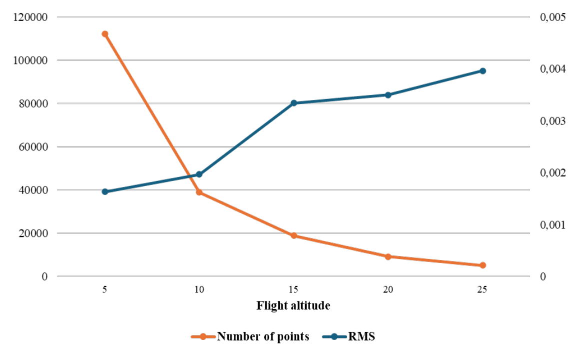


Figure 8. Trend of RMS values and point counts of dense clouds at different altitudes

Point cloud density, measured in points per square centimetre, decreases significantly with increasing altitude. At 5 m, the density is 14.62 points/cm², but at 25 m, it drops sharply to 0.68 points/cm², representing a 95% reduction. This loss of density creates challenges for road pavement monitoring, as high-density point clouds are crucial for accurately identifying cracks and surface defects. Lower densities at higher altitudes limit the ability to capture fine-scale irregularities and reconstruct the detailed geometry of the pavement surface, thereby reducing the overall reliability and precision of the analysis (Figure 8).

The graphical assessment of point distances between the reference cloud and clouds generated at varying altitudes reveals a distinct pattern. At lower altitudes, errors are primarily localised in specific areas, such as the cracks under analysis. However, as altitude increases, these errors become more widespread, extending across the entire surface. This phenomenon is attributed to the reduced resolution of images captured at higher altitudes, which limits the software’s ability to detect discontinuities and reconstruct geometric details in adjacent areas reliably.

A critical parameter further examined is the mean radius calculated for each point cloud, representing achievable geometric precision (Table 5, Figure 9).

Altitude (m)	Default radius (mm)
Ground Truth	0,004494
5	0,006516
10	0,011208
15	0,015882
20	0,022696
25	0,029974

Table 5. Default radius values calculated by CloudCompare as survey altitude increases.

More specifically it is defined as the radius of a sphere centered on each point of the dense cloudes. This radius increases with altitude, ranging from 0.006516 mm at 5 m to 0.029974 mm at 25 m. Larger radii correspond to greater positional uncertainty of points relative to the actual surface, significantly limiting measurement accuracy. This limitation is particularly problematic for road pavement distress monitoring, where precision on the order of millimetres is necessary to assess surface defects effectively.

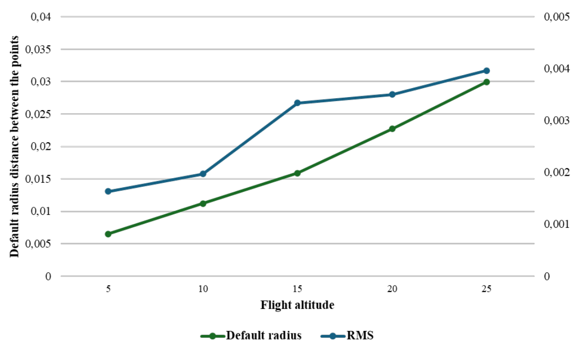


Figure 9. Default radius values calculated by CloudCompare as survey altitude increases.

The results illustrated in Figure 9 provide critical insights into the progressive impact of flight altitude on the geometric precision of the point clouds. The default radius, a key metric calculated for each point cloud, demonstrates a clear increasing trend as the altitude rises. At 5 m, the radius is approximately 0.006516 mm, representing a high level of precision suitable for detecting fine-scale pavement distress such as micro-cracks. However, as the altitude increases, the default radius grows significantly, reaching

0.029974 mm at 25 m. This trend reflects a substantial decline in the resolution and accuracy of the captured data, highlighting the trade-off between altitude and the ability to reconstruct detailed surface geometries.

This increase in the default radius indicates a broader spatial dispersion of points in the cloud, which correlates with the loss of density observed in the results. The greater the default radius, the higher the uncertainty in the spatial positioning of points, leading to a less reliable representation of the pavement surface.

The influence of altitude on the default radius also suggests a diminishing capacity to capture abrupt changes in surface geometry, such as the edges of cracks or depressions. At lower altitudes, the smaller radius allows for sharper and more defined transitions in the data, enabling a clearer delineation of defect boundaries. In contrast, at higher altitudes, the broader radius likely smooths out these transitions, making it more difficult to distinguish between true surface defects and noise or artefacts introduced during the photogrammetric process.

6. Conclusions

This study systematically evaluated the influence of flight altitude on the accuracy and quality of drone-based photogrammetric surveys for road pavement monitoring. The results demonstrate a clear inverse relationship between altitude and both metric precision and spatial density of point clouds. At 5 m, Root Mean Square (RMS) values were as low as 0.0016 mm, with a point cloud density of 14.62 points/cm², reflecting high accuracy and detail. Conversely, at 25 m, RMS values increased to 0.0040 mm, while point density dropped to 0.68 points/cm², indicating a 143% rise in error and a 95% reduction in density.

The findings highlight the critical role of low-altitude surveys in ensuring sufficient accuracy for detecting and analysing fine-scale surface defects, such as longitudinal cracks. At lower altitudes, errors remain localised to specific features, whereas at higher altitudes, they extend across the entire surface, compromising the geometric fidelity of the point cloud. This trend is further supported by the progressive increase in mean radius values associated with point clouds at greater altitudes, signalling reduced precision in point positioning.

While lower-altitude surveys deliver the highest levels of accuracy, they also generate significantly larger datasets, requiring extended processing times and increased computational resources. These operational challenges underscore the importance of optimising flight parameters to balance the trade-offs between accuracy and efficiency. Survey planning should prioritise lower altitudes for applications requiring millimetric precision, while intermediate altitudes may be more suitable for broader, less detailed assessments.

The study provides a robust framework for improving drone-based photogrammetric workflows tailored to road pavement monitoring. Key recommendations include the adoption of precise flight planning methodologies to optimise image overlap and data quality, as well as the integration of advanced algorithms for efficient processing of high-density point clouds. These measures will ensure consistent and reliable geometric reconstructions for infrastructure management.

Future research should expand the scope of pavement distress types considered in drone-based surveys. While this study focused primarily on longitudinal cracks, other forms of distress, such as transverse cracks, alligator cracking, rutting, potholes, and surface roughness, should be included to validate and generalise the findings. Incorporating a wider range of defects will allow for a more comprehensive understanding of drone photogrammetry's capabilities and limitations in road pavement monitoring. Additionally, the exploration of adaptive technologies, such as automated distress classification and multi-sensor integration, could further enhance defect detection and characterisation.

In conclusion, this study demonstrates that carefully optimised drone photogrammetry provides a reliable and precise approach for road pavement monitoring, enabling high-resolution assessments that support effective infrastructure management and maintenance strategies.

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