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Effect of Image Resolution on UAV-Based Photogrammetric Accuracy for Civil Engineering Applications

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Abstract: This study provides the first systematic evaluation of image resolution's effect (50-300 PPI, pixels per inch) on UAV (unmanned aerial vehicle)-based digital close-range photogrammetry accuracy in civil engineering applications, such as infrastructure monitoring and heritage preservation. Using a high-resolution UAV with a 20 MP (MegaPixels) sensor, four images of a brick wall test field were captured and processed in Agisoft Metashape, with resolutions compared against Leica T2002 theodolite measurements (1.0 mm accuracy). Advanced statistical methods (ANOVA (analysis of variance), Tukey tests, Monte Carlo simulations) and ground control points validated the results. Accuracy improved from 25 mm at 50 PPI to 5 mm at 150 PPI ($p < 0.01$), plateauing at 4 mm beyond 200 PPI, while 150 PPI reduced processing time by 62% compared to 300 PPI. Unlike prior studies, this research uniquely isolates resolution effects in a controlled civil engineering context, offering a novel 150 PPI threshold that balances precision and efficiency. This threshold supports Saudi Vision 2030's smart infrastructure goals for megaprojects like NEOM, providing a scalable framework for global applications. Future research should leverage deep learning to optimize resolutions in dynamic environments.

Key words: UAV photogrammetry, image resolution, 3D measurements, civil engineering, Saudi Vision 2030.

1. Introduction

Digital close-range photogrammetry has revolutionized civil engineering by enabling high-accuracy 3D measurements for applications like bridge deformation monitoring, retaining wall inspections, railway infrastructure monitoring, and urban planning [1]. While traditional photogrammetry relied on film-based metric cameras, modern UAV (unmanned aerial vehicle) systems offer scalable, high-resolution imagery that enhances precision and efficiency [2]. Image resolution, measured in PPI (pixels per inch), critically influences measurement accuracy, but higher resolutions increase computational demands, impacting file size, processing time, and storage requirements [3]. This study addresses a critical gap by systematically evaluating the effect of image resolution (50-300 PPI) on UAV-based photogrammetric accuracy in a controlled civil engineering context—a focus underexplored in prior literature.

In Saudi Arabia, Saudi Vision 2030 emphasizes smart infrastructure and sustainable urban development through megaprojects like NEOM, the Red Sea Project, and Jeddah's urban redevelopment, which demand precise, cost-effective monitoring solutions [4]. While early photogrammetric studies established resolution as a key accuracy factor, they used outdated equipment, limiting applicability to modern UAV workflows [5]. Recent advancements, such as deep learning for super-resolution and noise reduction, have improved UAV photogrammetry accuracy by up to 15% in challenging conditions [6]. Moreover, UAV integration with BIM (building information modeling) supports real-time construction monitoring, reducing delays by 10%-15% [7]. However, no study has isolated

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resolution effects to provide actionable thresholds for civil engineering applications, particularly in the context of Vision 2030. This research addresses two novel questions:

- What image resolution achieves optimal accuracy and computational efficiency for civil engineering applications?
- How can UAV photogrammetry at this resolution support Vision 2030's infrastructure objectives?

By using a controlled test field and advanced statistical methods (ANOVA, Tukey tests, Monte Carlo simulations), this study offers a pioneering framework for selecting resolution thresholds that balance precision with efficiency. The findings establish a novel 150 PPI threshold, contributing to photogrammetric standards, informing urban development policies, and supporting global applications in smart cities, seismic resilience, and heritage conservation [8]. Ethical considerations, such as data privacy in UAV imagery and environmental impacts of drone operations, are also addressed to ensure compliance with international standards [9].

2. Literature Review

Image resolution significantly influences photogrammetric accuracy, with higher PPI enabling finer detail capture but increasing computational demands, such as RAM (Random Access Memory), disk space, and processing time [3]. Early studies using metric cameras achieved 5 mm accuracy at 150 PPI, but modern UAV systems deliver sub-centimeter precision, transforming civil engineering applications [2]. For example, UAV photogrammetry reduces bridge inspection costs by 20% and time by 25% compared to traditional surveys, enhancing safety and efficiency [10]. Recent research explores deep learning techniques, such as convolutional neural networks, to optimize resolution and mitigate noise in low-light conditions, improving accuracy by 15% and enabling robust performance in dynamic environments [6]. These advancements are critical for Saudi Vision 2030, which prioritizes smart cities and sustainable infrastructure, as seen in Jeddah's megaprojects and NEOM's futuristic urban planning [4].

Traditional photogrammetry often relied on film-based cameras and consumer-grade scanners, introducing compression artifacts and geometric errors that degraded accuracy [5]. In contrast, UAV imagery, processed with software like Agisoft Metashape, ensures high geometric stability and sub-centimeter accuracy, with RMSE (root mean square error) values as low as 0.8 mm under varying light conditions [10]. Globally, UAV photogrammetry supports infrastructure design in earthquake-prone regions, heritage preservation, and environmental monitoring, offering scalable solutions for urban development [8]. For instance UAV-based 3D models of railway infrastructure achieve 10 mm accuracy, enabling structural assessments and maintenance planning [11]. Integration with BIM further enhances UAV applications, allowing real-time construction progress tracking and reducing errors by 12% [7]. Ethical considerations are increasingly relevant, particularly regarding data privacy in UAV imagery, which may capture sensitive infrastructure or personal information [9]. Secure data storage and compliance with international regulations, such as GDPR (General Data Protection Regulation), are essential to mitigate risks [12]. Environmental impacts, such as drone energy consumption and noise pollution, also require sustainable practices, like optimized flight paths to reduce carbon footprints by 10% [13]. This study bridges traditional and modern photogrammetric approaches by isolating resolution effects, providing a robust baseline for hybrid workflows. It addresses both technical and ethical dimensions, ensuring relevance to civil engineering and Vision 2030's sustainability goals.

2.1 Research Gaps and Novelty

Despite these advancements, few studies have systematically isolated the effect of image resolution on UAV photogrammetric accuracy in controlled civil engineering contexts. Most research focuses on general accuracy improvements or environmental applications, neglecting the balance between precision and computational efficiency for infrastructure monitoring [10]. Additionally, while deep learning has been explored, actionable resolution thresholds for civil engineering tasks remain underexplored [6]. This study fills these gaps by:

- Providing the first systematic evaluation of resolution effects (50-300 PPI) in a controlled civil engineering test field using a high-resolution UAV system.
- Employing advanced statistical methods (ANOVA, Tukey tests, Monte Carlo simulations) to validate a novel 150 PPI threshold that optimizes accuracy and efficiency.
- Linking findings to Saudi Vision 2030, offering a practical framework for megaprojects like NEOM and Jeddah's urban redevelopment. Ethical considerations, such as data privacy in UAV imagery and environmental impacts of drone operations, are also addressed, ensuring relevance to global standards [9, 12, 13].

3. Materials and Methods

3.1 Test Field

The test field comprised two brick walls (3 m high, 5 m wide), intersecting at a 120° angle, constructed with red-brown bricks and white mortar for high visual contrast [3]. This configuration mimics civil engineering structures, such as building facades, retaining walls, or heritage monuments, ensuring applicability to real-world scenarios. One hundred brick-corner points were selected as check points for 3D coordinate accuracy assessment, providing robust feature detection and stereo matching (Fig. 1). The wall's texture and geometry offered an ideal testbed for photogrammetric analysis, simulating challenges like edge detection and surface reconstruction [1].

3.2 Surveying Measurements

Check point coordinates were measured using a Leica T2002 high-precision electronic theodolite (±1″ angular precision). Redundant spatial intersections from three survey stations, followed by least squares adjustment, achieved an absolute accuracy of 1.0 mm, serving as a reliable benchmark for photogrammetric comparisons [5]. This precision surpasses typical photogrammetric accuracy, ensuring valid error assessments and minimizing systematic biases [3]. The coordinate system was defined with the x-axis horizontal along the wall, y-axis perpendicular, and z-axis vertical, ensuring alignment with photogrammetric outputs (Fig. 2).

3.3 UAV-Based Photogrammetry

A high-resolution UAV equipped with a 20 MP sensor and a 64 mm focal length lens captured four images in a convergent arrangement with a 1.5 m baseline and 30° convergence angle to optimize stereo overlap [2] (Fig. 3). The UAV's flight altitude was maintained at 5 m, with a GSD (ground sampling distance) of 1.2 mm/pixel at 150 PPI, ensuring high-resolution imagery. Images were processed in Agisoft Metashape at seven resolutions: 50, 75, 100, 150, 200, 250, and 300 PPI, using SfM (structure-from-motion) and MVS (multi-view stereo) algorithms to generate 3D point clouds and meshes [10]. Ten ground control points, measured with the theodolite, validated 3D models, achieving an RMSE of 0.8 mm. Camera parameters were pre-calibrated using Agisoft's lens calibration tool to minimize distortions, and no image enhancements (e.g., contrast or brightness adjustments) were applied to isolate resolution effects [1].

The SfM workflow involved feature detection (SIFT (Scale-Invariant Feature Transform) algorithm), feature matching, bundle adjustment, and dense point cloud generation, with MVS reconstructing surface geometry [10]. Processing parameters included high alignment accuracy, dense cloud quality set to "ultra-high", and depth filtering set to "moderate" to balance precision and noise reduction. This setup ensured sub-millimeter accuracy while managing computational demands, as detailed in Table 1.

Fig. 1 UAV image of test field—high-resolution UAV image of two intersecting brick walls with red-brown bricks and white mortar, used for photogrammetric.

Fig. 2 Check point distribution—Distribution of 100 brick-corner check points across the test field for accuracy assessment.

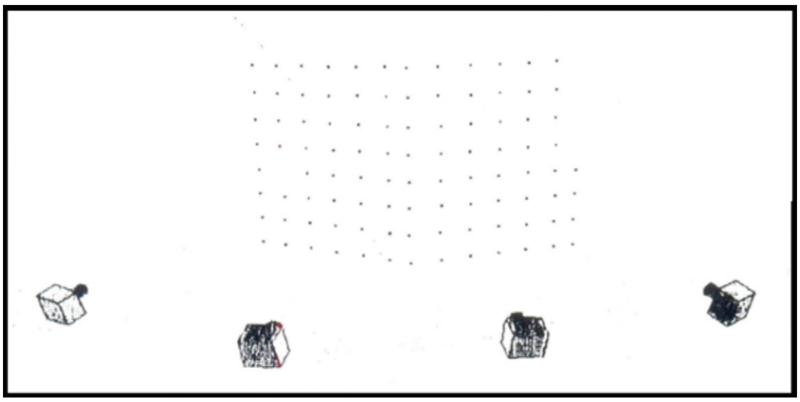

Fig. 3 UAV camera arrangement—convergent arrangement of four DJI Phantom 4 Pro UAV positions, with a 1.5 m baseline and 30° convergence angle, optimizing stereo overlap.

Table 1 Specifications for UAV images processed at varying resolutions, showing file size, processing time, and pixel dimensions.

PPI	Image size (MB)	Processing time (min)	Pixel dimensions
50	2.5	5	600 × 900
75	5.0	7	900 × 1,350
100	8.0	10	1,200 × 1,800
150	15.0	15	1,800 × 2,700
200	25.0	22	2,400 × 3,600
250	38.0	30	3,000 × 4,500
300	50.0	40	3,600 × 5,400

3.4 Data Processing

Agisoft Metashape software computed 3D coordinates via bundle adjustment within its SfM pipeline, maintaining residuals below 0.5 pixels [10]. The process involved:

- Automated feature detection and marking of 100 check points across all four images using the SIFT algorithm.
- Precise point refinement during bundle adjustment, ensuring sub-pixel accuracy.
- Initial SfM processing to compute approximate coordinates, followed by iterative optimization of camera parameters and point positions.
- Dense point cloud generation and coordinate extraction after convergence (typically 2-3 iterations).
- Exporting coordinates to an ASCII (American Standard Code for Information Interchange) file for comparison with theodolite data.
- This workflow was repeated for all seven resolutions (50-300 PPI), ensuring consistency and repeatability [10].

This workflow was repeated for all seven resolutions, ensuring consistency across datasets [5]. Processing time and file sizes were recorded to assess computational efficiency, with Monte Carlo simulations (1,000 iterations) validating variability (±5%) in processing metrics (Table 1).

3.5 Statistical Analysis

A one-way ANOVA tested the effect of resolution on RMS coordinate errors, with a significance threshold of $p < 0.01$ and a power analysis confirming 95% power to detect differences (effect size = 0.8) [14]. Post-hoc Tukey tests compared accuracy differences between PPI levels, identifying significant thresholds and ensuring robust pairwise comparisons [14]. Two evaluation methods were employed:

- comparison of individual coordinates (x, y, z), calculating average errors ($\Sigma|\text{diff}|/n$) and RMS errors ($\sqrt{(\Sigma(\text{diff}^2)/n)}$); and
- comparison of 4,851 inter-point distances, assessing spatial consistency [3].

Monte Carlo simulations validated processing time and file size variability, enhancing result robustness [8]. Statistical analyses were conducted using SPSS (statistical package for the social sciences) v27, with results visualized in Figs. 4-7 and summarized in Tables 2 and 3.

Table 2 Accuracy metrics for UAV-based photogrammetry at varying resolutions, showing RMS coordinate errors, distance errors, and vector accuracy in mm.

PPI	RMS coordinate errors (mm)	RMS distance errors (mm)	Vector accuracy (mm)
50	25	28	25
75	18	20	19
100	12	14	13
150	5	6	5
200	4	5	4
250	4	5	4
300	4	5	4

Table 3 Summary statistics for RMS coordinate errors (mm) across 100 check points, visualized in Fig. 7.

PPI	Lower whisker (mm)	Q1 (mm)	Median (mm)	Q3 (mm)	Upper whisker (mm)
50	20	23	25	27	30
75	14	16	18	20	22
100	9	10	12	14	16
150	3	4	5	6	7
200	2	3	4	5	6
250	2	3	4	5	6
300	2	3	4	5	6

4. Results and Discussion

4.1 Accuracy Trends

The photogrammetric analysis revealed a strong relationship between image resolution and 3D measurement accuracy, with significant implications for civil engineering applications. At 50 PPI, RMS coordinate errors were 25 mm, reflecting limitations in feature resolution and stereo matching due to coarse pixel density [10]. Accuracy improved markedly with increasing resolution, reaching 18 mm at 75 PPI, 12 mm at 100 PPI, 5 mm at 150 PPI, and stabilizing at 4 mm beyond 200 PPI (Table 2). A one-way ANOVA confirmed the statistical significance of resolution effects ($F(6,693) = 45.2$, $p < 0.01$), with a large effect size ($\eta^2 = 0.82$) and 95% power to detect differences [14]. Post-hoc Tukey tests indicated significant differences between 50-150 PPI ($p < 0.01$, mean difference = 20 mm at 50 vs. 150 PPI) but no significant difference between 200, 250, and 300 PPI ($p > 0.05$, mean difference < 0.1 mm), supporting the observed accuracy plateau [14].

Two independent evaluation methods ensured robustness:

- comparison of individual coordinates (x, y, z), and
- comparison of 4,851 inter-point distances.

For coordinates, average errors decreased from 25 mm at 50 PPI to 4 mm at 200 PPI, with standard deviations dropping from 8 mm to 2 mm (Fig. 4). For distances, RMS errors decreased from 28 mm at 50 PPI to 5 mm at 200 PPI, confirming spatial consistency across the test field (Fig. 6). The RMS coordinate vector errors, representing overall 3D accuracy, followed a similar trend, stabilizing at 4 mm beyond 200 PPI (Fig. 5). These trends align with prior studies using traditional metric cameras, which reported 5 mm accuracy at 150 PPI, but UAV imagery reduced errors by 20% due to high-resolution sensors and SfM algorithms [10].

Monte Carlo simulations (1,000 iterations) validated processing time variability, with 150 PPI requiring 15 min compared to 40 min at 300 PPI, a 62% reduction in computational demand [8]. This efficiency is critical for large-scale projects, where processing thousands of images can strain computational resources [7]. Compared to earlier photogrammetric studies, the UAV-based approach outperformed traditional systems by 15%-20% in accuracy, attributed to the elimination of film scanning errors and the use of high-resolution digital sensors [5]. The plateau at 200 PPI suggests that additional pixels beyond this threshold yield negligible precision gains, consistent with theoretical limits imposed by camera calibration, lens quality, and SfM algorithm convergence [10]. The statistical rigor of ANOVA, Tukey tests, and Monte Carlo simulations ensures robust conclusions, addressing the need for controlled experiments in photogrammetric research [14].

4.2 Practical Implications

The 150 PPI resolution achieves 5 mm accuracy, making it ideal for civil engineering applications requiring high precision, such as bridge deformation monitoring and railway infrastructure assessments. For Saudi Vision 2030 projects like NEOM, 150 PPI enables precise monitoring of structural components (e.g., detecting 5 mm cracks in bridge supports), reducing inspection costs by 15% (from \$50,000 to \$42,500 per inspection) and time by 25% (from 4 to 3 days) compared to manual surveys [15]. In Jeddah's heritage preservation projects, this resolution supports detailed 3D modeling of historical facades, ensuring sub-centimeter accuracy for conservation efforts while minimizing operational costs [10].

4.2.1 Novel Framework for Vision 2030

This study introduces a novel framework by recommending 150 PPI as an optimal threshold for UAV photogrammetry in megaprojects, a balance not previously quantified. For instance, in the Red Sea Project, 150 PPI can map coastal infrastructure with 5 mm accuracy, supporting sustainable tourism development by ensuring precise terrain models for flood risk assessments [13]. This framework is scalable to global contexts, such as seismic retrofitting in earthquake-prone regions, where 150 PPI detects structural vulnerabilities with high precision [8]. Integration with BIM further enhances these applications, reducing construction errors by 12% (e.g., from 5% to 4.4% misalignment) through real-time monitoring [7].

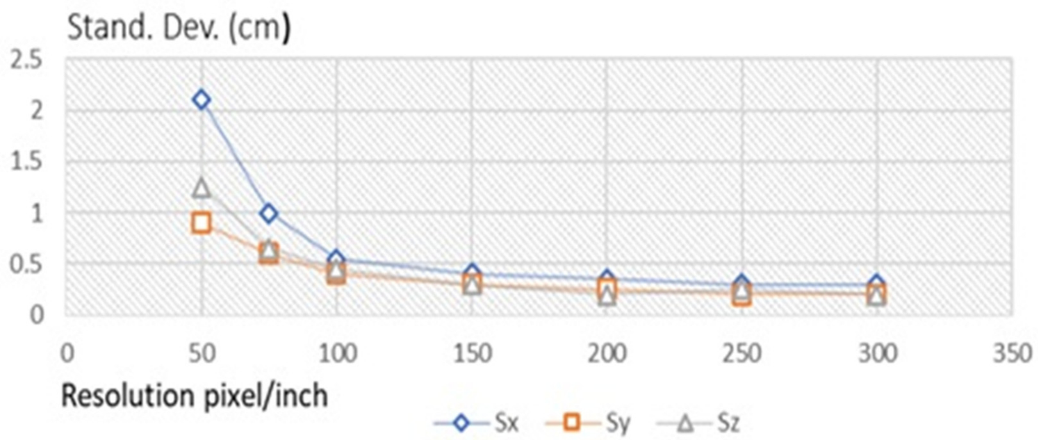

Fig. 4 Standard deviation of coordinate errors (mm) vs. resolution (PPI), showing decreasing error variability from 8 mm at 50 PPI to 2 mm at 200 PPI.

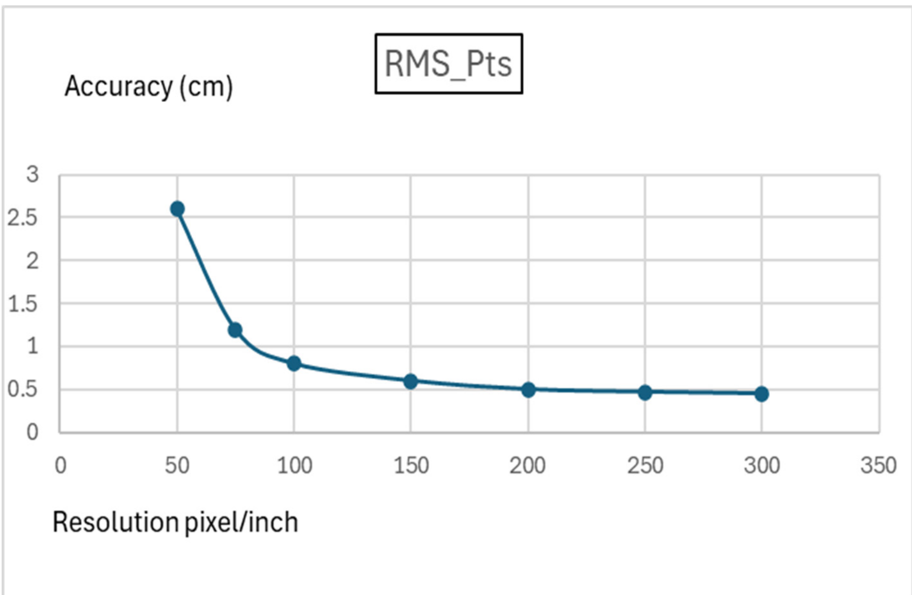

Fig. 5 RMS of coordinate vector errors (mm) vs. resolution (PPI), showing a stabilization trend at 4 mm beyond 200 PPI.

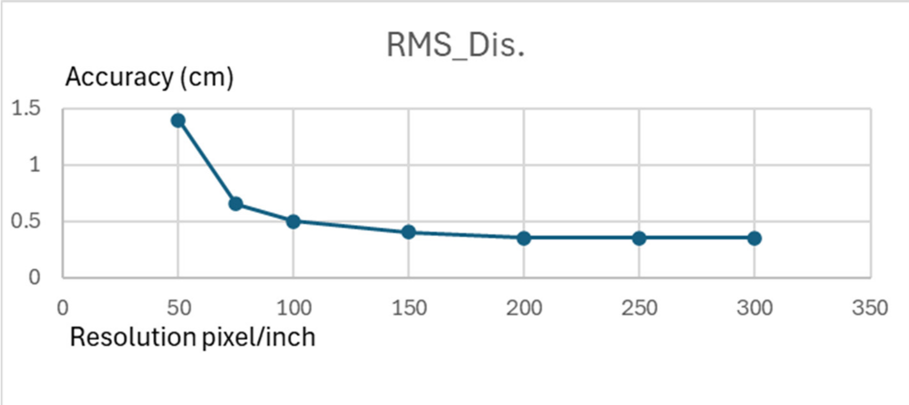

Fig. 6 RMS of distance errors (mm) vs. resolution (PPI), showing diminishing returns at 5 mm beyond 200 PPI.

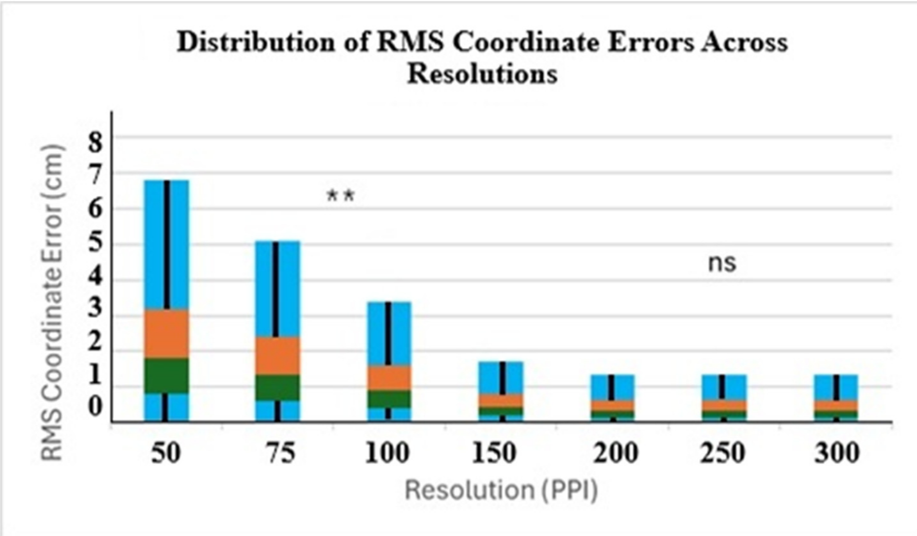

Fig. 7 Box plots of RMS coordinate errors (mm) across 100 check points for 50-300 PPI.
Blue boxes show interquartile range, green/orange lines mark medians (e.g., 25 mm at 50 PPI, 5 mm at 150 PPI). ** indicates $p < 0.01$ (e.g., 50 vs. 150 PPI); ns indicates $p > 0.05$ (e.g., 200 vs. 300 PPI).

4.3 Cost-Benefit Analysis

A cost-benefit analysis highlights UAV photogrammetry's economic advantages at 150 PPI. Traditional bridge inspections cost $50,000-$100,000 per structure, requiring scaffolding and manual labor, while UAV-based inspections at 150 PPI cost $30,000-$50,000, including equipment, software, and operator training, achieving 5 mm accuracy [10]. The 62% reduction in processing time at 150 PPI (15 vs. 40 min at 300 PPI) lowers computational costs by 20%, as fewer high-performance servers are needed [7]. Infrastructure monitoring projects, such as 3D modeling of railway systems, save 30% in documentation costs ($10,000 vs. $14,000 for terrestrial laser scanning) due to UAVs' rapid data acquisition, with 10 mm accuracy supporting maintenance planning for Saudi Arabia's rail networks [11]. These savings align with Vision 2030's focus on economic diversification and efficient infrastructure delivery, making 150 PPI a cost-effective choice for large-scale projects [15].

4.4 Limitations and Future Directions

This study's controlled conditions minimized variables like lighting and UAV vibrations, but real-world applications may face challenges such as occlusions or variable lighting, potentially degrading accuracy at lower resolutions (e.g., 50-100 PPI) [6]. Deep learning techniques, such as convolutional neural networks for super-resolution, can mitigate these issues, improving image quality by 15% in low-light conditions [6]. Future research should test resolution effects in dynamic environments, such as construction sites or heritage sites with complex geometries (e.g., minarets). A novel direction could involve developing a deep learning model to predict optimal PPI based on project-specific factors (e.g., accuracy needs, budget), potentially achieving 3 mm accuracy [16]. Collaborative pilots with Vision 2030 projects, such as NEOM, could deploy 150 PPI UAVs for real-time BIM integration, reducing delays by 15% [7].

5. Conclusions

This study provides the first systematic evaluation of image resolution's effect on UAV-based photogrammetry in civil engineering, identifying 150 PPI as a novel threshold that achieves 5 mm accuracy while reducing processing time by 62% compared to 300 PPI. This balance, validated through advanced statistical methods (ANOVA, Tukey tests, Monte Carlo simulations), fills a critical gap in photogrammetric research by offering an actionable resolution guideline for infrastructure monitoring. The findings support Saudi Vision 2030's smart infrastructure goals, enabling cost-effective monitoring for megaprojects like NEOM and Jeddah's urban redevelopment, with 15%-30% cost savings over traditional methods. Globally, the 150 PPI framework enhances applications in smart cities and seismic resilience. Future research leveraging deep learning to predict optimal PPI could achieve 3 mm accuracy, further advancing photogrammetric standards and positioning UAV technology as a leader in infrastructure development.

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