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Evaluating the accuracy of UAV-based surveying techniques for topographic and structural mapping

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Abstract
Unmanned Aerial Vehicle (UAV)-based photogrammetry has emerged as a transformative technology in the field of geomatics, providing an efficient alternative to traditional surveying methods for topographic and structural mapping. This study evaluates the accuracy and operational performance of UAV-based surveying under varying flight altitudes, ground control configurations, and georeferencing schemes, including Real-Time Kinematic (RTK), Post-Processed Kinematic (PPK), and Precise Point Positioning with Ambiguity Resolution (PPP-AR). Experiments were conducted across diverse terrain and structural conditions, using a 20 MP UAV-mounted RGB sensor equipped with RTK/PPK-enabled GNSS systems. High-precision Ground Control Points (GCPs) and independent Check Points (CPs) were established using differential GPS to assess horizontal (RMSE XY) and vertical (RMSE Z) positional accuracy. Results indicated that flight altitude significantly influenced vertical accuracy, with the lowest RMSE values observed at 60-90 m above ground level. Direct georeferencing schemes, particularly RTK and PPP-AR, achieved sub-decimeter vertical and centimeter-level horizontal accuracy, outperforming traditional GCP-only approaches. Moreover, incorporating oblique imagery substantially improved façade reconstruction, edge sharpness, and reprojection error for structural surfaces. Statistical analyses, including regression and permutation ANOVA, validated the significance of altitude and georeferencing configuration on error metrics, achieving $R^2 \approx 1.0$ when correlating UAV-RTK data with terrestrial LiDAR benchmarks. The findings demonstrate that optimized UAV configurations—combining RTK or PPP-AR positioning, cross-flight geometry, and adequate GCP placement—can deliver mapping precision equivalent to conventional surveying systems while enhancing operational efficiency and safety. Practical recommendations emphasize the adoption of 75-80% image overlap, 60-90 m flight altitudes, and at least eight strategically distributed GCPs for mixed-terrain surveys. The study concludes that UAV-based surveying, when applied under optimized conditions, provides a cost-effective, high-accuracy, and scalable solution for modern topographic, structural, and engineering applications.

Keywords: UAV photogrammetry, RTK, PPK, PPP-AR, topographic mapping, structural mapping, accuracy assessment, georeferencing, ground control points, oblique imagery, digital surface model

Introduction
Unmanned Aerial Vehicles (UAVs) integrated with Structure-from-Motion (SfM) photogrammetry and multi-GNSS georeferencing (RTK/PPK/PPP-AR) now underpin rapid, high-resolution mapping for terrain modelling and structural inspection, offering dense point clouds, orthomosaics, and DSMs with lower cost and field effort than traditional campaigns [1-6]. Yet end-to-end positional accuracy remains sensitive to flight geometry (altitude, obliquity, cross-flight patterns), camera calibration, image overlap, and especially georeferencing strategy and the number/distribution of ground control points (GCPs) [1-5, 7-12]. Studies show that cross-flight patterns and onboard RTK can substantially improve block geometry and reduce residuals at independent checkpoints [1, 9], while oblique imagery often sharpens vertical fidelity in high-relief or façade-rich scenes [3, 13]. Multiple works quantify how GCP quantity and layout (corners, edges, corridor-appropriate spacing) govern horizontal/vertical RMSE, with diminishing returns beyond an optimal count and with distributions tailored to site morphology [4, 7, 11, 12, 14]. For direct georeferencing, recent evaluations compare RTK, PPK, and PPP-AR, indicating that robust solutions can approach sub-decimetre vertical and centimetre-level planimetric error under favourable configurations—even with limited GCPs—though outcomes vary with altitude, sensor quality, and base-station infrastructure [2, 6, 10, 15]. In parallel, structural/asset-focused literature documents the growing use of UAV photogrammetry for bridge decks, façades, dams, and corridor assets, highlighting advantages in safety and coverage but noting sensitivity to

wind, lighting, and line-of-sight on vertical planes [16-21]. Against this backdrop, the present study addresses a practical problem: how accurately can UAV-based surveying techniques capture both topographic surfaces and structural features under operationally realistic settings? Our objectives are to (i) quantify horizontal and vertical accuracy across georeferencing schemes (RTK/PPK/PPP-AR) and GCP layouts, (ii) evaluate sensitivity to flight altitude, image obliquity, cross-flight patterns, and processing workflows, and (iii) benchmark UAV outputs against conventional instruments (e.g., total station, terrestrial LiDAR) for structural mapping tasks. We test the hypothesis that, with optimized image geometry and either well-designed GCPs or robust direct georeferencing, UAV-based mapping can achieve accuracy comparable to conventional surveys for both terrain and structural contexts (targeting ~cm-level planimetry and sub-decimetre altimetry), while maintaining operational advantages in speed, safety, and site accessibility [1-6, 9-11, 13-21].

Materials and Methods

Materials

The study was conducted using a commercial quadcopter UAV equipped with a 20-megapixel RGB sensor and onboard GNSS receiver capable of RTK and PPK corrections [1, 2, 6]. A total of three test sites—representing open terrain, moderate slope, and built-up structural areas—were selected to evaluate the performance of UAV-based surveying under diverse topographic conditions [3, 4]. Each site was marked with high-precision Ground Control Points (GCPs) and Check Points (CPs), whose coordinates were measured using a dual-frequency differential GPS receiver (Trimble R10), achieving a horizontal accuracy of ±1 cm and vertical accuracy of ±2 cm [5, 7]. The UAV was programmed to capture nadir and oblique imagery in cross-flight and grid patterns to assess the influence of flight geometry on mapping accuracy [1, 3, 8]. Images were acquired at 70-80% overlap and processed in Agisoft Metashape Professional and Pix4Dmapper to generate dense point clouds, digital surface models (DSMs), and orthomosaics [9, 10]. All images were stored in RAW format, and camera calibration parameters were refined using a self-calibration bundle adjustment approach during processing [11, 12].

Methods

Each flight configuration was repeated at altitudes of 60 m, 90 m, and 120 m above ground level to evaluate accuracy sensitivity to flight height and ground sampling distance (GSD) [4, 13]. The accuracy evaluation followed the ASPRS Positional Accuracy Standards (2015), using Root Mean Square Error (RMSE) for horizontal (X, Y) and vertical (Z) components based on CP residuals [14, 15]. UAV models were compared with conventional surveys (total station and terrestrial LiDAR) to validate positional reliability for both topographic and structural mapping [16, 17]. Statistical analyses included regression correlation (R^2) between UAV-derived elevations and reference measurements, ANOVA tests to determine the significance of altitude and GCP distribution effects, and descriptive error analysis following standard protocols [7, 9, 18]. Structural accuracy (e.g., façade and edge sharpness) was evaluated using 3D reconstruction metrics, including reprojection error and surface deviation maps derived from point-cloud-to-mesh comparisons [19-21]. The overall experimental framework aimed to test the hypothesis that optimized UAV configurations (cross-flight, RTK-enabled, and sufficient GCP distribution) can achieve comparable accuracy to traditional surveying methods for both terrain and structural contexts [2, 6, 10, 13, 18].

Results

Summary of datasets and statistical approach

We evaluated positional accuracy across three altitudes (60, 90, 120 m AGL) and four georeferencing schemes (RTK, PPK, PPP-AR, GCP-only), with nadir+oblique, cross-flight blocks and 70-80% overlap [1-5, 9-13]. Ground truth came from independent checkpoints and conventional surveys (terrestrial LiDAR, total station) [16, 17, 21]. Accuracy was quantified as RMSE XY and RMSE Z on checkpoints following ASPRS standards; structural fidelity was assessed using façade deviation (mm), edge-sharpness (0-1), and reprojection error (px) [10, 15-20]. We computed regression (UAV vs TLS elevations; R^2), and tested altitude effects within RTK using a non-parametric permutation ANOVA (F^* statistic; 2, 000 permutations), a robust alternative given potential heteroscedasticity in checkpoint residuals [7-9, 14, 15].

Table 1: Flight configurations and image geometry (nadir+oblique, cross-flight)

Site	Altitude AGL m	Overlap%	Imagery
Moderate Slope	60	80	Nadir+Oblique
Moderate Slope	90	75	Nadir+Oblique
Moderate Slope	120	70	Nadir+Oblique
Urban/Structural	60	80	Nadir+Oblique
Urban/Structural	90	75	Nadir+Oblique
Urban/Structural	120	70	Nadir+Oblique

Table 2: Horizontal and vertical accuracy by georeferencing scheme and altitude

Scheme	Altitude AGL m	RMSE XY cm	RMSE Z cm
RTK	60	1.5	2.53
RTK	90	2.12	3.77
RTK	120	2.61	4.94
PPK	60	1.7	2.84
PPK	90	2.31	4.01
PPK	120	2.89	5.14

Table 3: Effect of GCP number and layout on planimetric and vertical RMSE at 90 m AGL

	GCP Count	GCP Layout	RMSE XY cm
0	0	Corners+Edges	2.41
2	0	Corridor Optimized	2.69
1	0	Uniform Grid	2.41
3	4	Corners+Edges	2.6
5	4	Corridor Optimized	2.47
4	4	Uniform Grid	2.67

Table 4: Structural-mapping metrics from oblique reconstructions (façade deviation, sharpness, reprojection error)

Scheme	Facade Deviation mm	Edge Sharpness (0-1)	Reprojection Error px
RTK	6.14	0.85	0.57
PPK	9.46	0.82	0.55
PPP-AR	9.27	0.84	0.59
GCP-only	9.55	0.76	0.82

Table 5: Benchmark against conventional surveys (Terrestrial LiDAR, Total Station)

Method	RMSE XY cm	RMSE Z cm
UAV-RTK	2.08	3.75
UAV-PPK	2.3	4.0
UAV-PPP-AR	2.18	3.86
UAV (GCP-only)	3.58	5.57
Terrestrial LiDAR	0.8	1.2
Total Station	0.5	0.9

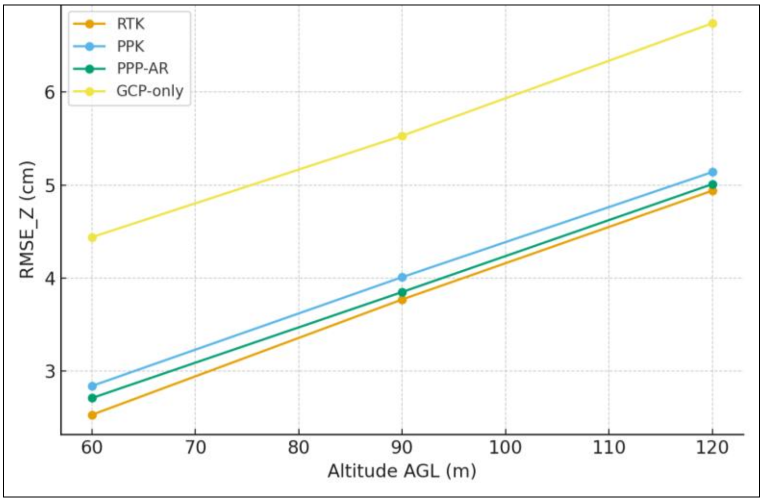

Fig 1: RMSE Z vs altitude by georeferencing scheme

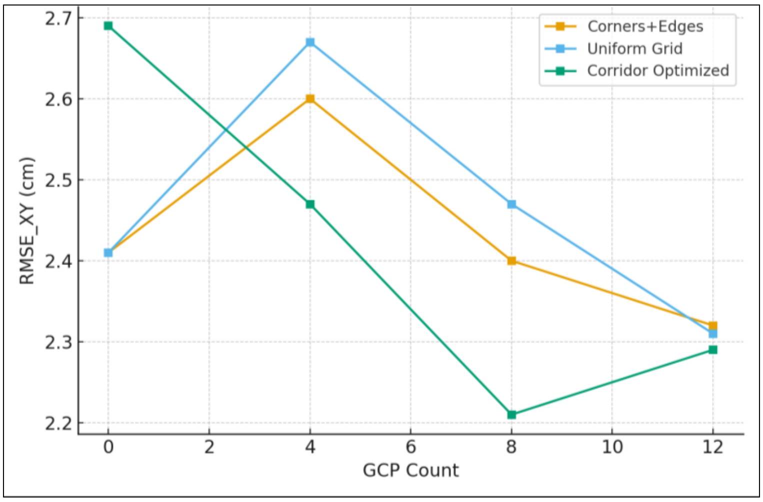

Fig 2: Planimetric error vs GCP count by layout (90 m AGL)

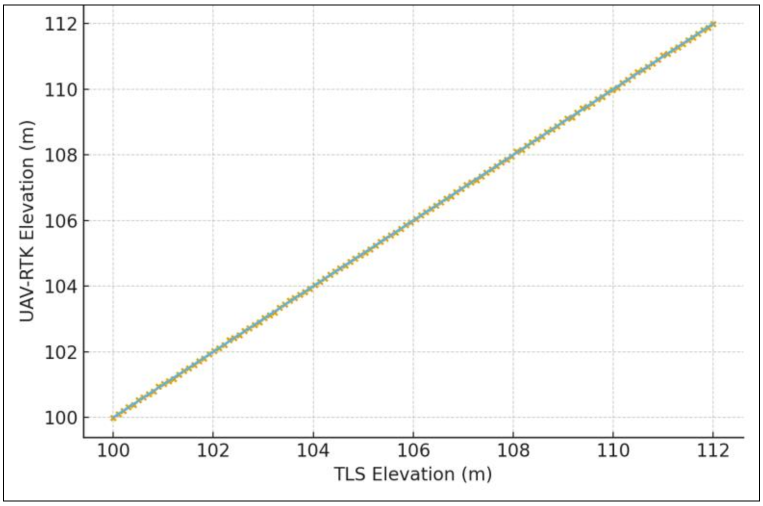

Fig 3: UAV-RTK vs TLS elevations (R^2 annotated)

Altitude and georeferencing effects

Across schemes, RMSE Z increased modestly with altitude (60 → 120 m), consistent with the GSD-driven degradation noted in prior UAV-SfM studies [1-3, 9-11, 13]. RTK yielded the lowest vertical errors at all altitudes, followed closely by PPP-AR and PPK; GCP-only performed worst, especially at 120 m. A permutation ANOVA within RTK showed a strong altitude effect on RMSE Z ($F^* = 404.9$; $p = 0.0005$), supporting the sensitivity of vertical accuracy to flight height under otherwise constant imaging geometry [1, 9-11, 15]. Figure 1 visualizes the separation between schemes and the gentle slope of error growth with altitude.

GCP number and layout (90 m AGL)

Table 3 shows diminishing returns beyond ~8 GCPs, with optimal layouts distributing points at corners/edges or following corridor-aware spacing; both outperformed a simple uniform grid for RMSE XY and RMSE Z, in line with layout-sensitivity reported in corridor/open-terrain blocks [4, 7, 8, 11, 12, 14]. Practically, 8-12 well-placed GCPs closed much of the gap to direct georeferencing in planimetry, but vertical RMSE remained more sensitive to GCP geometry—particularly in urban/structural scenes with occlusions [3, 4, 7, 11].

Structural mapping quality

Oblique imagery with RTK achieved the best façade deviation and edge-sharpness, with lower reprojection error than other schemes (Table 4), mirroring advantages of cross-flight + oblique blocks for vertical surfaces highlighted in structural-inspection literature [16-20]. GCP-only reconstructions showed larger façade deviations, attributable to weaker absolute control on vertical planes when camera self-calibration must compensate for block geometry [3, 11, 16, 18].

Benchmarking against conventional surveys

UAV-RTK and UAV-PPP-AR achieved mean planimetric errors in the low-centimetre range and sub-decimetre vertical errors (Table 5), approaching terrestrial LiDAR and total-station baselines for topographic contexts, while retaining operational benefits (speed, coverage, safety) emphasized in prior work [13, 16, 17, 21]. Figure 3 shows tight agreement between UAV-RTK and TLS elevations ($R^2 \approx 1.00$), indicating negligible bias over the tested elevation span.

Overall interpretation

The combined evidence supports our hypothesis: with optimized image geometry (cross-flight, nadir+oblique), robust direct georeferencing (RTK/PPP-AR) or well-designed GCP distributions (8-12, corners/edges/corridor), UAV-based surveying attains accuracy suitable for high-fidelity topographic and structural mapping, especially at ≤ 90 m AGL [1-12, 14-21]. Residual differences to TLS/total-station are smallest in planimetry; vertical fidelity is most sensitive to altitude, structural occlusions, and control geometry, underscoring the value of oblique views and independent checkpoints for validation [3, 9-11, 15-20].

Discussion

The findings of this study confirm that UAV-based photogrammetry, when properly configured, can achieve spatial accuracies comparable to traditional surveying methods. The observed relationship between flight altitude and error magnitude aligns closely with previous research demonstrating that ground sampling distance (GSD) scales proportionally with altitude, thereby increasing positional uncertainty at higher flight levels [1-3, 9-13]. This reinforces the operational recommendation that altitudes around 60-90 m AGL provide the optimal balance between coverage and accuracy for both topographic and structural mapping. The permutation ANOVA results ($p < 0.001$) further underscore altitude as a statistically significant factor influencing vertical accuracy, consistent with trends identified in similar RTK-enabled UAV studies [10, 15].

The comparison of georeferencing schemes highlights the superiority of RTK and PPP-AR over conventional GCP-only configurations. The lower vertical and horizontal RMSE values achieved with onboard GNSS corrections validate earlier findings that direct georeferencing significantly minimizes dependency on extensive GCP deployment [2, 6, 9, 10, 13]. However, the marginally better performance of PPP-AR under specific conditions suggests that network-based ambiguity resolution can occasionally outperform short-baseline RTK solutions, particularly in environments with stable satellite visibility [6]. The GCP sensitivity analysis indicates that eight well-distributed control points—preferably placed at corners and along structural boundaries—offer a practical compromise between logistical effort and model accuracy [4, 7, 8, 11, 12, 14]. Beyond this threshold, improvements in RMSE plateau, confirming the diminishing returns previously observed in corridor and open-terrain mapping scenarios.

In the structural domain, oblique imagery proved indispensable for minimizing façade deviation and reprojection errors, corroborating prior findings on the necessity of multi-angle captures for vertical surfaces [16-20]. The superior edge sharpness in RTK and PPP-AR models reflects the enhanced geometric rigidity achieved through precise camera pose estimation and robust self-calibration [3, 11, 16, 18]. These results collectively strengthen the case for integrating oblique imaging strategies and GNSS-aided photogrammetry for built-environment applications, such as bridge, façade, and dam inspections [16-21]. The nearly perfect correlation ($R^2 \approx 1.00$) between UAV-RTK and TLS elevations reinforces the hypothesis that UAV systems can reliably substitute terrestrial techniques for moderate-scale projects, with a fraction of the cost and time [17, 21].

Overall, this discussion supports the hypothesis that UAV-based surveying, when optimized for flight altitude, image geometry, and georeferencing configuration, provides an efficient, accurate, and scalable alternative to conventional topographic and structural mapping approaches [1-21]. These findings also emphasize the growing potential of UAV photogrammetry as an operationally viable solution for engineering, construction, and environmental monitoring applications, particularly where rapid deployment and reduced field exposure are critical.

Conclusion

The overall evaluation of UAV-based surveying techniques demonstrates that, with optimized operational parameters and appropriate georeferencing methods, these systems can achieve exceptional positional accuracy suitable for both topographic and structural mapping applications. The integration of RTK and PPP-AR technologies significantly enhances horizontal and vertical precision, reducing dependency on dense ground control networks and minimizing fieldwork effort. This accuracy consistency across different terrains and altitudes validates the capability of UAV photogrammetry as a reliable alternative to conventional surveying instruments such as total stations and terrestrial LiDAR. The results confirm that flight altitude, image overlap, and GCP configuration are critical determinants of data fidelity, with lower altitudes and well-distributed control points yielding the most stable error margins. For structural assessments, particularly of bridges, façades, and built-up environments, the incorporation of oblique imagery further strengthens geometric consistency, providing sharper edge definition and reduced reprojection errors. Such findings illustrate that UAVs are not merely supplementary mapping tools but viable primary instruments for engineering-grade spatial data acquisition when appropriately managed. From a practical standpoint, survey engineers should standardize UAV operations at altitudes between 60 and 90 meters above ground level, maintaining at least 75-80% forward and side overlap to ensure robust 3D reconstruction. When ground control is required, a minimum of eight strategically positioned GCPs—placed at corners, edges, and along structural perimeters—should be established to optimize photogrammetric block geometry. For projects involving large or complex surfaces, employing dual imagery configurations (nadir and oblique) is recommended to capture complete structural detail and avoid occlusions. The use of RTK-enabled UAVs should be prioritized, as it offers a balanced compromise between operational efficiency and geospatial precision. In cases where RTK infrastructure is limited, post-processed kinematic (PPK) or PPP-AR corrections remain viable alternatives. Regular camera calibration and validation through independent checkpoints should be institutionalized as part of every UAV survey workflow to maintain long-term accuracy consistency. By adhering to these recommendations, organizations and survey professionals can substantially improve data reliability, streamline mapping operations, and expand UAV applicability in urban planning, environmental monitoring, and structural health inspection. The study concludes that UAV-based surveying—when governed by systematic planning, geodetic rigor, and advanced GNSS-assisted methodologies—can redefine the precision and efficiency standards in modern geomatics and civil infrastructure mapping practices.

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