

The influence of ground control point placement and UAV platform on the accuracy of photogrammetrically derived orthomosaics and digital elevation models

Jakub Ceglarek¹  0000-0003-0444-7072

Marcin Kamieniczny¹  0009-0004-8057-5134

¹ Faculty of Geographic and Geological Sciences, Adam Mickiewicz University in Poznań

✉ Corresponding author: jakub.ceglarek@amu.edu.pl

Summary

Photogrammetry has proven to be a valuable technique across various industries, particularly in construction and surveying, due to its capacity to generate high-resolution orthomosaics and digital elevation models (DEMs). The emergence of unmanned aerial vehicles (UAVs) has further revolutionized photogrammetric practices, offering an efficient means to create various geospatial products. This study delves into the accuracy of orthomosaics and DEMs derived from UAV-based photogrammetry, with a specific focus on the impact of ground control point (GCP) placement strategies. The research examines how different GCP configurations influence the precision of photogrammetric products. By comparing outputs from three distinct UAV models, the study highlights the combined influence of GCP distribution and UAV technical specifications on the accuracy of the resulting data. The findings indicate that strategic GCP placement can substantially enhance the quality and precision of photogrammetric outputs. Moreover, the selection of the UAV platform significantly affects resolution and processing efficiency. This study underscores the critical role of careful GCP placement within the UAV photogrammetry workflow to ensure the reliability of generated products. Optimal GCP deployment is essential for achieving accurate georeferencing and minimizing errors stemming from GPS inaccuracies, lens distortion, and insufficient image overlap. The research contributes to a deeper understanding of how to balance precision and efficiency in UAV photogrammetry by analyzing the trade-offs associated with various GCP placement strategies. These insights are particularly valuable for practitioners aiming to optimize project outcomes while considering budget constraints and accuracy requirements.

Keywords

photogrammetry • unmanned aerial vehicles (UAV) • ground control points (GCPs) • digital elevation models (DEMs) • accuracy assessment

1. Introduction

The rapid evolution and adoption of photogrammetry – a technique that uses geometric information from 2D imagery – has revolutionized data acquisition in fields such as reconstruction [Lee et al. 2024], agriculture [Lawrence et al. 2023], virtual reality environment [Karnchanapayap et al. 2024], archaeology [Forte et al. 2025], surveying and environmental monitoring [Briggs et al. 2018]. Although the roots of photogrammetry date back to the 19th century, when aerial photos were taken from the hot-air balloons, its swift development and transition to digital processes has significantly expanded its accuracy, speed and range of applications. Unmanned aerial vehicles (UAV) made photogrammetry more accessible, cost-effective, and facilitated the generation of high-resolution orthomosaics, digital elevation models (DEMs) and 3D reconstructions with centimeter-level accuracy [Colomina and Molina 2014]. The lowering cost of UAVs has not only shortened acquisition time but also made the technology more accessible to users who could not afford it previously. The reliability of these outputs depends on multiple factors, such as drone sensor quality, flight parameters, and crucially the deployment of ground control points (GCPs) [Lee et al. 2024]. Furthermore, the role of environmental factors, such as sunlight variation, terrain complexity and wind, must also be considered when assessing overall data quality. This study examines how different UAV platforms and GCP configurations influence the accuracy of photogrammetric outputs providing an overall view for industry practitioners. Traditional surveying methods, such as total stations and terrestrial laser scanning (TLS), are time-consuming in case of large-scale projects [Beretta et al. 2018]. In contrast, UAV photogrammetry offers quick data collection, lower costs, and the ability to access hazardous or inaccessible areas, such as open pit mines [Suh and Choi 2017]. However, limitations such as restricted flight time due to battery life, weather dependency, limited payload capacity, the necessity of safe battery storage, and regulatory restrictions (e.g., operations Beyond Visual Line of Sight (BVLOS)), continue to pose challenges to the UAV adoption. Further development in structure-from-motion algorithms and cloud processing with software like Pix4D, Agisoft Metashape have made the technology accessible even for non-specialists [Almagro 2002]. SfM techniques allow users to create 3D models and orthomosaics from uncalibrated image sets, reducing technological barriers for non-expert users and simplifying access to high-quality spatial data. Physical markers with known coordinates are critical for georeferencing and eliminating errors caused by GPS inaccuracies, lens distortion or insufficient image overlap [Zhong et al. 2025]. Drones equipped with the RTK systems can minimize the effect of GCP dependence, however, their higher cost may present a significant barrier for adoption in developing regions or for small-scale projects [Štroner et al. 2025]. In addition, post-processing kinematic (PPK) solutions offer an alternative to RTK by reducing real-time communication needs but still demand expertise and financial investments. Studies suggest that GCP quantity, distribution and measurement precision directly impact output quality, but optimal configurations remain unconventional and debated [Lawrence et al. 2024]. For instance, Amami et al. in their study stated that one GCP over 8000 square meters

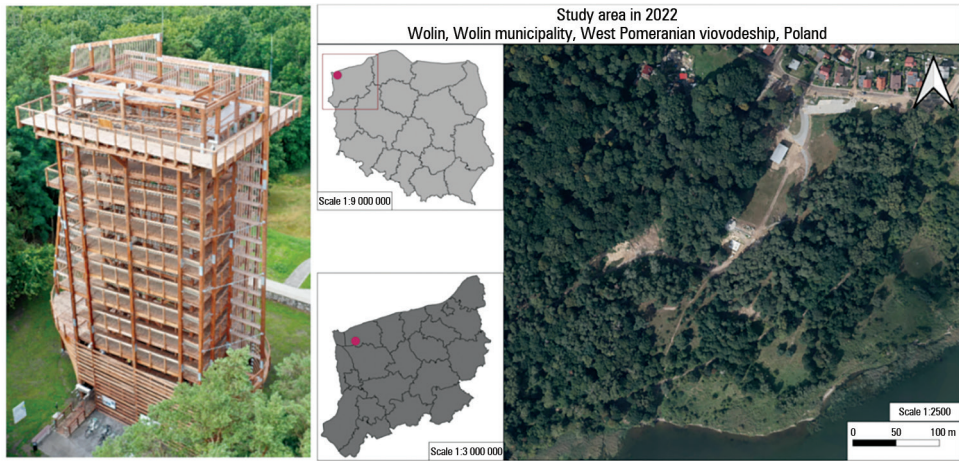
is sufficient to provide highly robust geometry [Amami et al. 2022] while Oniga et al. in their study recommend one GCP per 200 square meters for geographically complex terrain [Oniga et al. 2018]. These differences among researchers highlight the need for standardized guidelines, as GCP deployment strategies may vary significantly depending on terrain complexity, vegetation density and required final product accuracy. In the construction industry, UAVs play a major role in progress monitoring, volumetric calculations and as-built documentation, but require sub-centimeter accuracy for clash detection. In such applications where high quality and high precision data are imperative, even minor inaccuracies can cause costly delays for projects, emphasizing the importance of carefully designed GCP networks and rigorous quality control workflows. Regulatory standards often mandate third-party validation of photogrammetric outputs, underlining the GCP's rigor. In forestry applications, where changing lighting and vegetation cover obstruct feature matching, appropriate GCP strategies are necessary [Iglhaut et al. 2019]. Seasonal variations, density of tree canopies and undergrowth characteristics further complicate photogrammetric processing. Such scenarios require an adaptive approach to GCP placement and data acquisition timing. Despite extensive literature on UAV photogrammetry, few studies compare consumer-grade versus RTK drones across multiple GCP scenarios in real-world conditions [Madawalagama and Munasinghe 2016]. A practical comparison is essential for users to make correct decisions with regard to equipment investments, workflow optimization and expected levels of accuracy in different photogrammetric scenarios. This study aims to quantify how GCP placement influences the quality of orthomosaic and DEM outputs in the context of coordinates errors. This research contributes to optimizing photogrammetric workflows for practitioners balancing precision and efficiency, using consumer-grade UAV without RTK receivers. Specifically, the research will analyze the trade-offs between precision and various GCP placement strategies, contributing valuable insights for users aiming to balance project constraints, budget limitations and accuracy requirements.

2. Methods

2.1. Study area

For the purpose of this survey, a newly constructed observation tower located in the town of Wolin, in the Zachodniopomorskie voivodeship, Kamień county, was selected. The structure was officially opened to the public in March 2024. The wooden construction consists of 11 levels, reaching a total height of 32 meters. The shape of the viewing platform was designed to resemble a sail, while the base structure was supposed to form a ship's hull. The object is built from wooden beams, which create significant gaps within the structure, posing considerable challenges during photogrammetric reconstruction.

The observation tower is situated on the summit of a small hill, surrounded by tall coniferous trees. The photogrammetric flight was initially scheduled for July 10, 2024,



Source: Authors' own study

Fig. 1. Observation tower – survey object and location map

at 12:45 PM. Due to a thunderstorm, the flight time was postponed to 5:45 PM. After the storm, the sky was covered with dense clouds, which significantly diffused the sunlight in the atmosphere. As a result, no distinct shadows were cast by any objects, preventing large fluctuations in ISO values when capturing images in automatic mode. The air temperature during the survey was 25°C, wind gusts did not exceed 2.5m/s, and atmospheric pressure remained unstable due to the passing storm over Wolin Island on July 10. All unmanned aerial vehicles (UAVs) were launched at five-minute intervals to ensure the most consistent atmospheric conditions for each flight.

2.2. Drones used in the survey

Three UAVs from DJI (Shenzhen DJI Sciences and Technologies Ltd., China, 2006) were used to perform the photogrammetric flights: a) Mavic 2 Pro, b) Air 2S and c) Mini 3. The camera parameters for each drone are presented in Table 1.

Table 1. Drones used in the survey

	DJI Mini 3	DJI Air 2S	DJI Mavic 2 Pro
Sensor	1/1,3" 12MP	1" 20MP	1" 20MP
Lens	82,1°	88°	77°
Focal length	24 mm	22 mm	28 mm
Aperture	f/1.7	f/2.8	f/2.8–f/11
ISO	100–3200 (auto)	100–6400 (auto)	100–3200 (auto)

The hovering accuracy for all UAVs was ± 0.5 meter vertically and ± 1.5 meter horizontally. All cameras were pre-mounted by the manufacturer on three-axis gimbals to ensure stability.



Source: Authors' own study

Fig. 2. Photos of the drones

3. Methods

3.1. Data acquisition

The photogrammetric flight plan included the establishment of a ground control network as well as manual orbiting around the object at two altitudes: 36 meters and 51 meters above ground level (AGL). The decision to fly manually was based on the fact that not all aircraft could be configured for autonomous flight. Each UAV used different control application: Mavic 2 Pro was controlled with 'DJI GO 4', Air 2S was flown with an app built-in into RC-Controller and Mini 3 with 'DJI Fly'. Photographs were manually captured after stabilizing the drone at each position. A total of 249 images were taken with each UAV. Ground control points were established to georeference the images collected by all platforms, using a GNSS receiver. The control points were measured with a Trimble GNSS receiver (Trimble Inc., Westminister, Colorado, USA, founded in 1978), model R6. The PL-2000 coordinate system for the 15th meridian East, EPSG:2176, was chosen for measurement, and real-time corrections were obtained from the VRSNet network. Control points were measured both on the ground and on the observation deck of the tower.

3.2. Photogrammetric processing

3.2.1. Align photos

The photogrammetric data were processed using Agisoft Metashape (Agisoft Metashape, St. Petersburg, Russia, established 2010), version 2.0.2. The EPSG:2176 coordinate system for the 15th zone was assigned to the project. A custom script was developed to modify the height parameter of the drone images to correct the originally recorded camera center coordinates. The images recorded the AGL (above ground level) height by default. However, the creation of a digital terrain model (DTM) and compatibility with GCP required the ASL (Above Sea Level) heights. Therefore, the altitude values for all platforms were converted from AGL to ASL. All reference points were divided

into five sets, differing in the included GCPs, allowing for accuracy comparisons across selected scenarios (Table 2).

Table 2. GCP usage scenarios

Scenarios	Ground control points	Tower control points	Drone
#1 full set	×	×	×
#2 ground and tower	×	×	
#3 only ground	×		
#4 only tower		×	
#5 drone			×

For the purposes of the study, three groups of control points were distinguished:

- ‘Ground control points’ were the points measured on the ground using a GNSS receiver, stabilized with wooden stakes.
- ‘Tower control points’ were the points measured on the observation deck of the survey object.
- ‘Drone’ refers to the use of the camera center coordinates recorded by the UAV during the flights.

The root mean square error (RMSE) was calculated to assess the deviation in the X and Y coordinates in each scenario relative to the GNSS-measured control points. The results were compared across the designed scenarios. For comparative analysis of the generated digital terrain models (DTMs), an available reference DTM for the study area was utilized (sourced from www.geoportal.gov.pl). A DTM with a 0.5-meter resolution, created in 2022, was downloaded. Ten points located in the immediate vicinity of the observation tower were selected for the analysis. The coordinates of these points were first determined by the reference DTM and subsequently projected onto the DTMs generated according to each scenario. Due to the presence of tall vegetation, it was not possible to measure control points directly underneath the tower using the GNSS receiver. The Trimble receiver was unable to receive sufficient satellite signals to obtain RTK corrections under the dense canopy. As a result, ground control points were measured as close to the tower as possible within the receiver’s capability.

3.2.2. Dense cloud

Dense point clouds were generated based on tie points. In the ‘Advanced’ tab, the default parameters were used for processing the clouds: ‘key point limit’ was set to 40,000 and ‘tie point limit’ to 4,000. The point clouds allowed for the calculation of the orthophotos and digital terrain models.

3.2.3. DEM

The source data for creating the digital terrain models were the previously generated dense point clouds. Point clouds were chosen primarily due to their very high accuracy

in representing the 3D scene, in contrast to the tie point clouds, which are sparser and result in lower-quality digital terrain models.

3.2.4. Orthomosaics

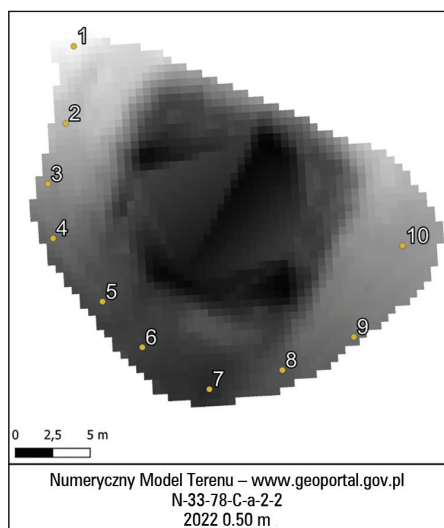
Orthomosaics were created using all images taken by each drone and the coordinate reference system EPSG: 2176 was used. The digital terrain model corresponding to each scenario was selected as the base layer for orthophoto generation. The option to fill in empty areas was enabled, and the pixel size was kept at 0.018 meters for Mini 3, 0.014 meters for Air 2S and 0.012 for Mavic 2 Pro.

3.3. Scenario Comparison

The comparison of the scenarios was based on the calculated RMSE for each case. The coordinate error results for control points in fifteen scenarios are presented in Table 3 and Table 4.

3.3.1. Orthomosaics comparison

The comparison of the resulting orthophotos was carried out based on the calculated RMSE values for previously measured control points. The measured control points were cataloged and placed on the orthophotos. Then, for each scenario, a vector layer was created, consisting of points located at the original positions of the control points as measured using a GNSS receiver. The statistical significance of the findings was tested using ANOVA analysis of variance.



Source: Authors' own study

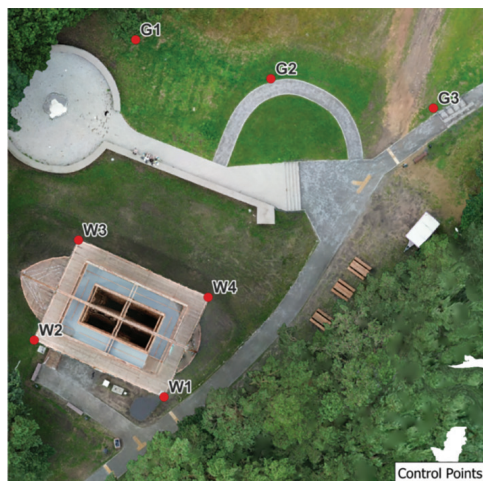
Fig. 3. Digital elevation model downloaded from www.geoportal.pl with the layer of control points used in the survey

3.3.2. DEM comparison

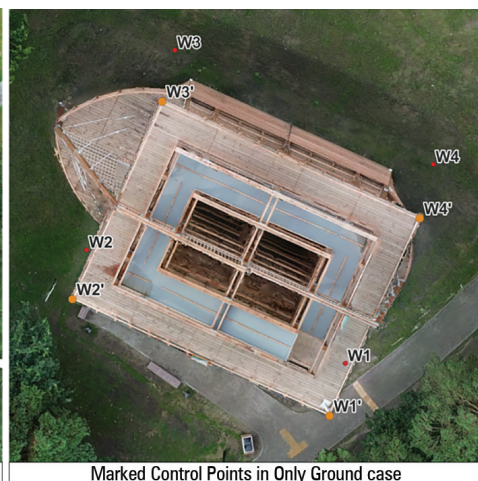
The comparison of digital elevation models was based on the created point vector layers representing ten selected measurement points for each scenario. Unlike the orthophotos, the coordinates of the points were left unchanged to highlight differences between scenarios with different GCP placement strategies and also to highlight the differences in vertical axis between sets.

4. Results

The computer used for processing was equipped with a six-core AMD Ryzen 5 3500X processor (www.amd.com) and a NVIDIA RTX 3060Ti 8 GB graphics card (www.nvidia.com). The study results revealed significant differences in accuracy depending on the selected ground control point deployment scenario. Photogrammetric products based solely on ground control points demonstrated a noticeable deterioration in the coordinates accuracy of points located on the elevated parts of the surveyed structure. Conversely, scenarios relying only on control points placed on the tower showed considerable deviations in the coordinate accuracy for ground control points. The scenario that combined both ground and tower control points achieved the lowest discrepancies, when compared to the reference data. In contrast, the scenario with no ground control points – relying exclusively on the GNSS module data from various drones – exhibited substantial coordinate inaccuracies at all evaluated points, regardless of the drone model. A total of 15 scenarios were calculated based on the previously created GCP distribution sets (Table 3 and Table 4).



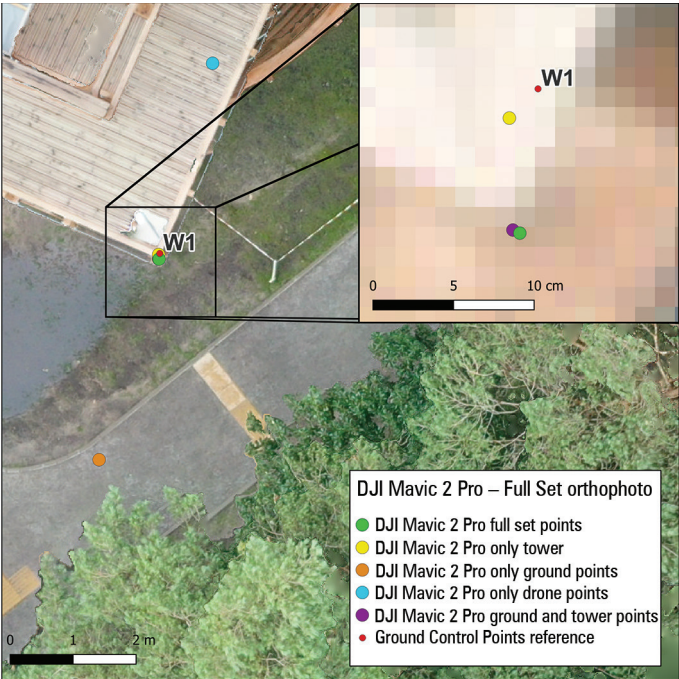
Source: Authors' own study



Source: Authors' own study

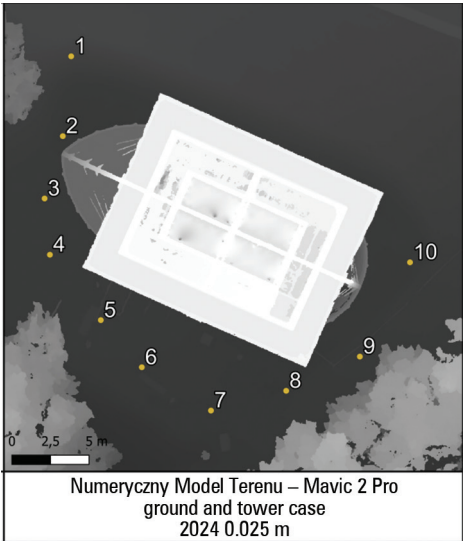
Fig. 4. Control points

Fig. 5. Marked control points



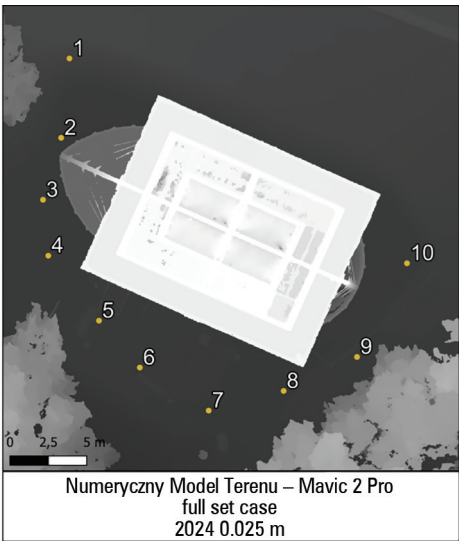
Source: Authors' own study

Fig. 6. W1' coordinates in various scenarios



Source: Authors' own study

Fig. 7. Mavic 2 Pro ground and tower scenario



Source: Authors' own study

Fig. 8. Mavic 2 Pro full set scenario

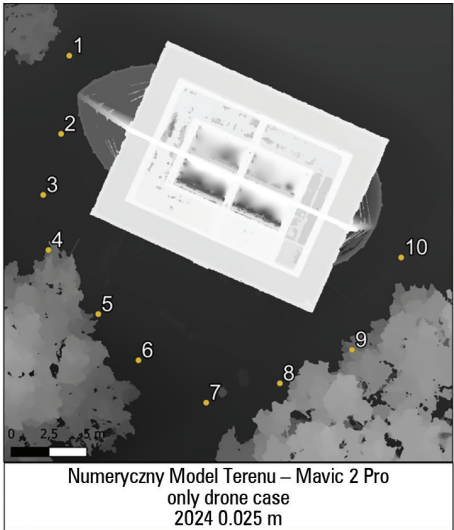
Table 3. Orthomosaics horizontal errors for all UAVs and scenarios (in meters)

Point ID	Full set				Ground and tower				Only ground				Only tower			Only drone		
	Mavic 2 Pro	Mini 3	Air 2S		Mavic 2 Pro	Mini 3	Air 2S		Mavic 2 Pro	Mini 3	Air 2S		Mavic 2 Pro	Mini 3	Air 2S	Mavic 2 Pro	Mini 3	Air 2S
G2	0.037	0.032	0.023		0.031	0.033	0.018		0.019	0.028	0.027		0.288	0.278	0.292	4.574	2.398	2.151
G3	0.031	0.039	0.057		0.030	0.045	0.052		0.020	0.014	0.027		0.341	0.320	0.368	4.629	2.679	2.362
W1	0.086	0.075	0.092		0.089	0.064	0.090		3.413	3.024	2.936		0.026	0.024	0.034	3.132	2.365	2.113
W2	0.042	0.034	0.046		0.043	0.024	0.030		3.203	2.832	2.731		0.011	0.005	0.008	3.285	2.164	1.979
W3	0.082	0.070	0.080		0.086	0.053	0.084		3.310	2.926	2.807		0.008	0.002	0.006	3.493	2.162	1.996
W4	0.070	0.028	0.076		0.069	0.036	0.075		3.466	3.073	2.955		0.027	0.027	0.017	3.399	2.398	2.176

Table 4. Digital Elevation Model elevation errors for all UAVs and scenarios, compared to the reference height (in meters)

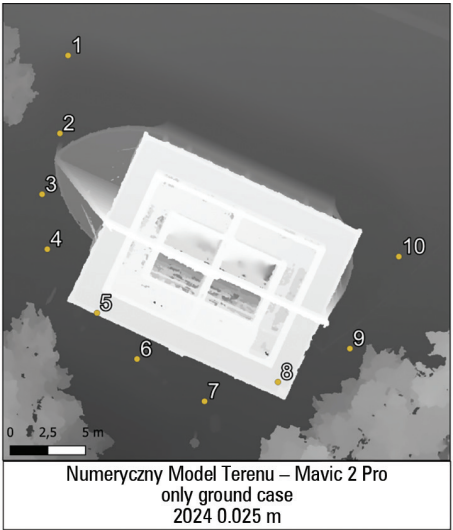
Point ID	Full set				Ground and tower				Only ground				Only tower			Only drone		
	Reference	DJI Mavic 2 Pro	DJI Mini 3	DJI Air 2S	DJI Mavic 2 Pro	DJI Mini 3	DJI Air 2S		DJI Mavic 2 Pro	DJI Mini 3	DJI Air 2S		DJI Mavic 2 Pro	DJI Mini 3	DJI Air 2S	DJI Mavic 2 Pro	DJI Mini 3	DJI Air 2S
1	17.53	0.302	0.276	0.257	0.299	0.277	0.255		3.671	3.226	3.109		0.106	0.104	0.102	3.302	1.172	3.330
2	16.76	0.726	0.710	0.700	0.727	0.714	0.709		4.475	4.027	3.863		0.591	0.601	0.570	2.837	1.069	2.997
3	16.25	0.110	0.069	0.091	0.107	0.084	0.093		4.478	3.939	3.793		-0.036	-0.062	-0.049	2.440	0.495	2.499
4	15.76	-0.408	-0.405	-0.419	-0.407	-0.407	-0.424		4.491	3.860	3.711		-0.550	-0.598	-0.565	2.060	0.018	2.032
5	15.37	-0.820	-0.794	-0.820	-0.825	-0.822	-0.820		-21.816	-23.440	-23.670		-0.993	-0.968	-0.986	2.065	-0.327	1.756
6	15.23	-0.833	-0.882	-0.832	-0.831	-0.866	-0.828		4.595	3.871	3.662		-1.017	-1.018	-0.956	2.377	-0.196	1.889
7	15.01	-0.889	-0.945	-0.853	-0.892	-0.939	-0.853		5.195	4.475	4.229		-1.078	-1.112	-1.092	1.915	-0.292	2.036
8	15.53	-0.323	-0.350	-0.336	-0.321	-0.351	-0.334		-21.330	-21.900	-22.123		-0.498	-0.494	-0.506	1.909	0.040	2.363
9	15.89	-0.262	-0.331	-0.303	-0.262	-0.331	-0.315		5.011	4.337	4.162		-0.425	-0.463	-0.475	-7.095	0.138	2.566
10	16.27	0.143	0.123	0.028	0.142	0.121	0.027		4.470	3.936	3.641		0.007	0.011	-0.100	1.805	0.499	2.843

The measurements of 10 points on the digital terrain model generated using the ‘only ground’ scenario from Table 2 revealed significant discrepancies at points 5 and 8. These inaccuracies were caused by major distortions of the surveyed structure, which was not located in close proximity to any two reference points. A similar situation occurred for the Mavic 2 Pro platform in the ‘only drone’ scenario at point 9.



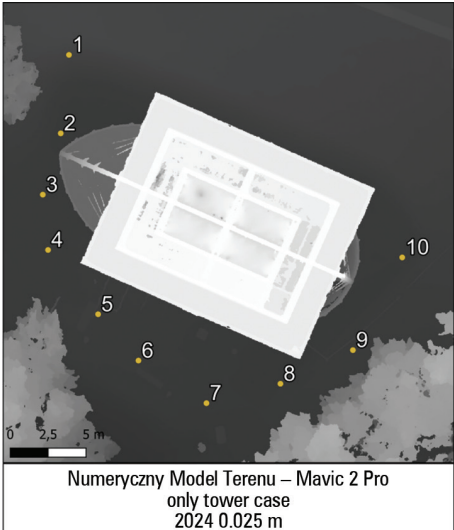
Source: Authors’ own study

Fig. 9. Mavic 2 Pro only drone scenario



Source: Authors’ own study

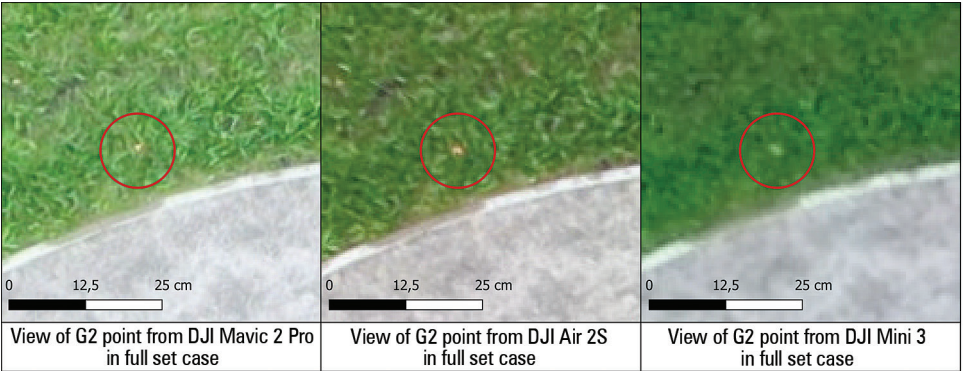
Fig. 10. Mavic 2 Pro only ground scenario



Source: Authors’ own study

Fig. 11. Mavic 2 Pro only tower scenario

The scenario in which the digital terrain model deviated from the vertical was related to the automatic adjustment of processing to the model's center. The ground control points placed on the ground were located far from the tower, causing a shift in the data relative to the center. The selected measurement points, whose coordinates remained unchanged, appeared to be incorrectly mapped within the tower's geometry. This explains why points 5 and 8 show such large value jumps (Table 2). The DJI Mini 3 had the lowest resolution, making it difficult to align the marker properly with a point of known coordinates. The lower resolution meant that greater precision was required for image alignment due to the marker being harder to recognize (Fig. 12).



Source: Authors' own study

Fig. 12. Various views of G2 point from different drones to highlight camera resolution differences

A statistical analysis was performed to evaluate the significance of GCP configurations and UAV platforms. Their influence on the final photogrammetric outputs P-values was measured for the same drone in different scenarios. It was observed that for Mavic 2 Pro and Air 2S results significantly affected the orthomosaics accuracy ($p < 0.05$). However, no statistically significant differences were found in the DEM outputs for any of the UAVs, with p-values circulating around 1 for Mavic 2 Pro and Air 2S and 0.356 for Mini 3 (Table 5).

Table 5. P-value results for the same drones and different scenarios

	Mavic 2 Pro	Air 2S	Mini 3
P-value ortho	0.019	0.037	0.113
P-value dem	0.926	0.993	0.356

The second test evaluated the influence of different UAV platforms under the same GCP scenario. In this case, no statistically significant differences were observed between drone models in any GCP configuration. For orthomosaics, p-values ranged

from 0.42 to 0.99, and for DEMs from 0.24 to 0.99, confirming that drone choice did not significantly impact the accuracy of outputs when the GCP layout remained the same (Table 6 and Table 7).

Table 6. P-value results for the same scenarios and different drones for orthomosaics

	p-value
Full set	0.831
Ground and tower	0.795
Ground	0.421
Tower	0.993
Drone	0.911

Table 7. P-value results for the same scenarios and different drones for DEMs

	p-value
Full set	0.992
Ground and tower	0.992
Ground	0.776
Tower	0.820
Drone	0.239

Discussion

The results of this study highlight the growing importance of photogrammetry among industries that require high-precision geospatial data, such as construction, land surveying and lidar mapping [Kovanič et al. 2023]. The comparative analysis of various drone platforms and GCP configurations provides a valuable insight into how to optimize accuracy and increase efficiency for consumer-grade drone photogrammetric products. One of the most crucial findings of the survey is the importance of correct distribution of GCPs that directly influences the quality of photogrammetric products. The study confirms that uniform GCP coverage across the surveyed area plays a major role in minimizing RMSE. The study demonstrates their impact. Scenarios in which drone GNSS coordinates were the only source for aligning photos (without GCP) exhibited errors. This confirms what Sanz-Ablanedo et al. found in their study that standalone GNSS modules are incapable of submeter accuracy [Sanz-Ablanedo et al. 2018]. These observations align with previous research conducted by Agüera-Vega et al., which emphasizes that GCPs should be evenly placed across the entire surveyed area, and not concentrated in a single point to ensure minimal distortions [Agüera-

Vega et al. 2017]. The study also evaluated how different drone models affect output quality. RTK-equipped drones provide significantly less dependence on GCP compared to platforms without one. Consumer-grade drones (e.g., DJI Mavic 2 Pro, DJI Mini 3, DJI Air 2S) can achieve sub-decimeter accuracy when supported by sufficiently dense GCP network, making them suitable for projects that do not require a high level of data accuracy. Previous research conducted by Molnar showed that consumer-grade drones are a good option in measuring land mass volume on construction sites, where GCPs are already placed [Molnar 2016]. This study underscores that the strategy for placing GCPs should be project-specific. In this study, the observation tower played a significant role in optimal GCP placement. It was demonstrated that vertical objects force GCP placement to be more distributed across all axes. Large-scale topographic surveys may force the user to provide data with RTK-equipped device to avoid placing vast amount of GCPs, which means further time-consuming aligning processes. A hybrid approach that combines a RTK drone with a minimal number of GCPs may be optimal for certain projects [Nesbit et al. 2019]. While this study only focused on optical photogrammetry, future investigations could compare the results with LiDAR-based datasets, particularly in urban environments that afford numerous vertical objects. This study could be repeated with GCPs placed specifically within a close range of investigated object with newer GNSS receiver. This discussion reinforces that photogrammetric accuracy is not only dependent on equipment but rather on an approach integrating drone capabilities with suitable GCP placement and mission planning. Drone technology evolves and so do practices of combining different methods for obtaining maximum effectiveness and desired accuracy across various industries.

The statistical results support the hypothesis that the configuration of ground control points has a significant impact on orthomosaic accuracy. The lack of statistical significance in DEM accuracy across scenarios suggests that vertical accuracy is less sensitive to GCP distribution compared to horizontal orthophoto precision. Additionally, the lack of significant differences between drone models with the same GCP setups shows that, in this context, GCP placement plays a more critical role in determining photogrammetric accuracy than the choice of UAV platform.

Conclusions

This study analyzed the critical role of accurate GCP placement in enhancing the quality of high-resolution orthomosaics and digital elevation models in various scenarios. The results highlight the importance of choosing the optimal drone platform and the configuration of ground control points. Various configurations regarding GCP placement can significantly influence the accuracy of photogrammetric outputs. The results should be divided into two groups – orthomosaics errors and digital elevation model errors. Scenarios with well-distributed GCPs across the entire survey area consistently resulted in lower RMS errors, indicating higher accuracy. In contrast, sets where GCPs were unevenly distributed across the entire survey area (e.g. only tower points or only ground points) resulted in insufficient correction and generated signifi-

cant distortions and higher errors. The orthomosaic scenario in which no GCPs were used during orthomosaic generation ('only drone' scenario) showed significant errors. Conversely, scenarios without internal drone GPS coordinates used during processing showed better results and lower displacement. Similar results have been observed for digital elevation model scenarios. Sets where GCPs were placed inaccurately exhibited significant distortions. On the other hand, sets that used better GCP placement strategy ensured better results and more accurate elevation models. Acquiring high-precision products is demanded and inevitable in the outputs used by construction or 3D modelling industries. Optimal GCP placement minimizes output distortions and improves overall accuracy, ensuring that the outputs meet the defined requirements of professional applications. The choice between high-end and consumer-grade UAV platforms plays a significant role in the quality of the outputs. This study shows that even with lower-grade UAVs without RTK modules it is possible to achieve desired output quality. In the future, the study could be repeated with a drone that provides RTK fixes on coordinates to see whether the quality of RTK output could be matched with regular module drone platform.

References

- Agüera-Vega F., Carvajal-Ramírez F., Martínez-Carricondo P. 2017. Assessment of photogrammetric mapping accuracy based on variation ground control points number using unmanned aerial vehicle. *Measurement*, 98, 221–227. <https://doi.org/10.1016/j.measurement.2016.12.002>
- Almagro A. 2002. Simple methods of photogrammetry: easy and fast. https://www.academia.edu/92063140/Simple_Methods_of_Photogrammetry_Easy_and_Fast
- Amami M., Elmehdwi A., Borgaa A., Buker A., Alareibi A. 2022. Investigations into utilizing low-cost amateur drones for creating ortho-mosaic and digital elevation model. *International Research Journal of Modernization in Engineering Technology and Science*. March, 4(3), 2107–2118.
- Beretta F. et al. 2018. Topographic modelling using UAVs compared with traditional survey methods in mining. *REM-Int. Eng. J.*, 71(3), 463–470. <https://doi.org/10.1590/0370-44672017710074>
- Briggs R., Thibault C., Mingo L. 2018. Usage of unmanned aerial vehicles for iceberg surveying and monitoring – Preliminary results. In: *Proc. OTC Arctic Technol. Conf.*, 28–29 March 2018. <https://doi.org/10.4043/29132-MS>
- Colomina I., Molina P. 2014. Unmanned aerial systems for photogrammetry and remote sensing: A review. *ISPRS J. Photogramm. Remote Sens.*, 92, 79–97. <https://doi.org/10.1016/j.isprsjprs.2014.02.013>
- Forte A. et al. 2025. Geomatics and metaverse for lost heritage sites documentation and dissemination: The case study of Palmyra Roman Theatre (Syria). *Virtual Archaeol. Rev.*, 16(32), 85–99. <https://doi.org/10.4995/var.2024.21662>
- Iglhaut J. et al. 2019. Structure from motion photogrammetry in forestry: A review. *Curr. For. Rep.*, 5, 155–168. <https://doi.org/10.1007/s40725-019-00094-3>
- Karnchanapayap G., Somboon P. 2024. Revolutionizing art exhibitions: Photogrammetry's role in virtual reality experiences. *Humanit. Arts Soc. Sci. Stud.*, 825–837. <https://doi.org/10.69598/hasss.24.3.267821>

- Kovanič E. et al. 2023. Review of photogrammetric and lidar applications of UAV. *Appl. Sci.*, 13(11), 6732. <https://doi.org/10.3390/app13116732>
- Lawrence I., Agnishwar J., Vijayakumar R. 2023. Drone technology in agriculture for surveillance and inspection. *Eur. Chem. Bull.*, 12 (special issue), 1253–1263. <https://doi.org/10.48047/ecb/2023.12.si12.113>
- Lee E. et al. 2024. Enhancement of low-cost UAV-based photogrammetric point cloud using MMS point cloud and oblique images for 3D urban reconstruction. *Measurement*, 226, 114158. <https://doi.org/10.1016/j.measurement.2024.114158>
- Madawalagama S. et al. 2016. Low cost aerial mapping with consumer-grade drones. In: *Proceedings of the 37th Asian Conference Remote Sensing*, Colombo, Sri Lanka, 17–21 October 2016.
- Molnar A.N.D., Domozi Z.S., 2016. Volume analysis of surface formations on the basis of aerial photographs taken by drones. *Int. J. Signal Process. Image Process. Pattern Recognit.*, 1, 152–159.
- Nesbit P.R., Hugenholtz C.H. 2019. Enhancing UAV – SfM 3D model accuracy in high-relief landscapes by incorporating oblique images. *Remote Sens.*, 11(3), 239.
- Oniga V.-E., Breaban A.-I., Statescu F. 2018. Determining the optimum number of ground control points for obtaining high precision results based on UAS images. *Proceedings*, 2(7). <https://doi.org/10.3390/ecrs-2-05165>
- Sanz-Ablanedo E. et al. 2018. Accuracy of unmanned aerial vehicle (UAV) and SfM photogrammetry survey as a function of the number and location of ground control points used. *Remote Sens.*, 10(10), 1606. <https://doi.org/10.3390/rs10101606>
- Suh J., Choi Y. 2017. Mapping hazardous mining-induced sinkhole subsidence using unmanned aerial vehicle (drone) photogrammetry. *Environ. Earth Sci.*, 76, 1–12. <https://doi.org/10.1007/s12665-017-6458-3>
- Štroner M. et al. 2021. Photogrammetry using UAV-mounted GNSS RTK: Georeferencing strategies without GCPs. *Remote Sens.*, 13(7), 1336. <https://doi.org/10.3390/rs13071336>
- Zhong H. et al. 2025. Influence of ground control point reliability and distribution on UAV photogrammetric 3D mapping accuracy. *Geo-Spat. Inf. Sci.*, 1–21.

<https://doi.org/10.1080/10095020.2025.2451204>

<https://doi.org/10.3390/rs11030239>

www.dji.com

www.agisoft.com

www.geoportal.gov.pl

www.amd.com

www.nvidia.com