Examining the Impact of Ground Control Point Quantity on the Geometric Accuracy of UAV Photogrammetric Products Formed Using Structure-from-Motion Approach

RATKO R. NIKOLIĆ, University of Belgrade,
Faculty of Civil Engineering, Belgrade
NENAD D. BRODIĆ, University of Belgrade,
Faculty of Civil Engineering, Belgrade
BRANKO S. BOŽIĆ, University of Belgrade,
Faculty of Civil Engineering, Belgrade

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The positional and vertical accuracy of UAV aerial photogrammetry products generated using the Structure from Motion (SfM) approach depends on various factors, such as flight plan parameters, camera quality, camera calibration, the SfM algorithm used, and the georeferencing process. The influence of the quantity of Ground Control Points (GCPs) on the geometric quality of generated models and the stability of camera calibration parameters assessed through self-calibration in the block-aerotriangulation process was investigated in this study. Three software systems were used to process the collected UAV photogrammetry images: Pix4D Mapper, Agisoft Metashape, and Trimble Inpho UASMaster. Standard statistical quality assessments were employed to assess the accuracy of the block-aerotriangulation. The research findings indicate that augmenting the quantity of GCPs enhances model reliability and decreases the RMSE values of vertical deviation on the control points. The RMSE values of vertical deviation on the check points for all three used software systems converged to approximately twice the value of the average spatial resolution. Additionally, the RMSE values of positional deviation on check points converged to the value of the average spatial resolution.

Key Words: *UAV photogrammetry, Structure-from-Motion, Ground Control Points, Check points, Bundle Block Adjustment*

1. INTRODUCTION

In the last decade of this century, new possibilities in the field of mass spatial data collection have brought remote-controlled aircraft commonly referred to as „unmanned aerial vehicles“ (UAVs).The International Civil Aviation Organization (ICAO) introduced the term „Remotely Piloted Aircraft Systems“ (RPAS), stating that UAS is a broader concept that encompasses all systems without a physically present pilot [1].

Therefore, remotely piloted aircraft are a subgroup of unmanned aircraft that require a control station and communication technology for remote aircraft operation.

Generally, it is a technology in the form of an aerial platform that does not have a physically present human crew but is operated by a ground-based operator. The aircraft is equipped with navigation sensors and optical sensors for collecting aerial imagery.

Simultaneously with the development of these systems, there has been progress in the development of high-resolution digital sensors that are compact, efficient, and find increasing applications in photogrammetry. It is questionable whether cameras mounted on UAV systems can be used for photogrammetric purposes, that is, whether they provide high-quality images without significant lens distortions.

Alongside the aforementioned advancements, the development of digital photogrammetry has also progressed in terms of efficient georeferencing of amateur images, automatic generation of 3D models of captured objects and obtaining various other photogrammetric products that were previously reserved for conventional photogrammetry applications.

The quality of UAV photogrammetry products is

Author’s address: Ratko Nikolić, University of Belgrade, Faculty of Civil Engineering, Belgrade, Bulevar kralja Aleksandra 73

e-mail: nikolic.ratko@outlook.com

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influenced by several key factors, including:

- Use of calibrated cameras (calibration method, stability of internal orientation parameters, sensor and lens quality, shutter type, etc.);
- Quality of photogrammetric images (spatial resolution, sharpness, contrast, etc.);
- Parameters of the flight plan, which define the UAV photogrammetric block (longitudinal and transverse overlap, flight altitude, etc.);

The georeferencing process of collected images involves a set of actions necessary to spatially position the images in the appropriate coordinate system. In the field of photogrammetry, the process of image orientation traditionally relies on a specific dataset of points known as GCPs, whose coordinates are known in the corresponding coordinate system. These GCPs are mapped onto the corresponding images according to a pre-established photogrammetric survey plan [2].

Evaluating the geometric accuracy of the generated models has confirmed that the arrangement and accuracy of the GCPs play a vital part in the formation of a high-quality, accurate, and reliable 3D model using the Structure-from-Motion (SfM) approach [3].

2. RELATED WORK

Harwin et al. conducted a study in [4] to explore how different quantities of GCPs affect the accuracy of block aerotriangulation using the Structure-from-Motion approach. Initially, five GCPs were included in the processing, with one point placed at the center of the study area. Subsequently, additional GCPs were evenly distributed through the study area, and in the second experiment, a total of 13 ground control points were utilized. The results of the analysis using RMSE on the GCPs indicate that using a larger number of GCPs enables achieving higher positional and elevation accuracy of the photogrammetric point cloud.

Sanz-Ablanedo et al. in [5] also examined how varying distributions and quantities of GCPs affect the quality of photogrammetric outcomes. The study area in this research was significantly larger, covering 1.225 km^2, compared to the previously mentioned publication. By increasing the quantity of GCPs employed in the block aerotriangulation process iteratively, ranging from three to a final total of 101 points, block aerotriangulation was performed, and RMSE values of deviations at the GCPs and CPs were estimated. With a significant number of GCPs, the planimetric accuracy stabilized at the average GSD of the input images, while the altimetric accuracy reached twice the value of the GSD.

In the research performed by Oniga et al. in [6], the exploration of the optimal quantity of GCPs for attaining highly precise outcomes in UAV imagery georeferencing was examined. UAV images were acquired over a 1-hectare area using a low-cost UAV-DJI Phantom 3 at two different flight altitude: 28 meters and 35 meters above surface level. The total station was used to measure coordinates of 50 GCPs, and the UAV images were processed utilizing two separate software systems: 3DF Zephyr Pro and Pix4D Mapper. By gradually increasing the quantity of GCPs from three to 40, the researchers assessed the geometric accuracy of the generated models. At a height of 28 m, utilizing Pix4D software system, the RMSE decreased significantly from 81 cm with the minimum number of 3 GCPs to an impressive 2 cm with 40 GCPs, validating the importance of an increased number of GCPs for enhanced accuracy. Similarly, when employing 3DF Zephyr Pro software, the RMSE reduced from 49 cm to 2.5 cm for the same height range. Additionally, at a height of 35 m, the optimum GCPs for both software systems were 15, leading to sub-decimetre accuracy.

In a case study conducted by Ulvi in [7], a mine site was selected as the research site. The researchers investigated how the distribution of GCPs affected the geometric accuracy of this 2590-hectare project. They compared three scenarios, namely edge distribution, central distribution, and a homogeneous distribution of GCPs. The results indicated that the highest planimetric accuracy was achieved with GCPs distributed on the edges ($RMSE_{xy}$ = 0.033 m), while the best altimetric accuracy was attained with a homogeneous distribution ($RMSE_z$ = 0.048 m). The findings suggest that a combination of GCPs placed through the center and edges of the research site yields the most accurate results. Furthermore, the research demonstrated that the precision of orthophotos and DSMs generated through UAV photogrammetry significantly improves with careful consideration of both the quantity and distribution of GCPs. This research provides valuable insights for future large-scale UAV projects, optimizing the positioning of GCPs to achieve high-quality results while minimizing time and costs spent on land surveys.

3. MATERIALS AND METHODS

Figure 1 depicts the study's process. The research consists of four primary stages: planning the route (including in-situ survey, pre-flight preparations, and configuring flight parameterss), acquiring data (GNSS survey, conducting UAV image acquisition), processing data with varied number of GCPs, and assessing horizontal and vertical quality (including data analysis and error evaluation).

The research was concluded by comparing the coordinates of GCPs and CPs measured on-site with the corresponding map coordinates obtained through data processing.

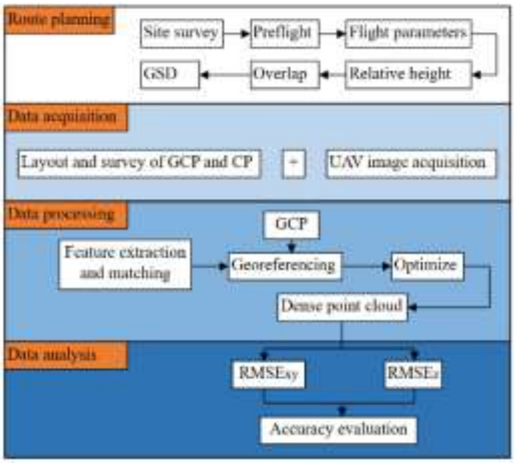

Figure 1 - Research Workflow

3.1. Study Area

All measurements in this research are presented in meters and are referenced to UTM Zone 34N (World Geodetic System 1984 ensemble, WGS84). The study area is located in area of the Altina neighborhood in Belgrade (Figure 2). The area spans about 1 hectare, reaching its highest point at 86 meters and lowest at 79 meters. It encompasses railways, parking areas, and a playground.

Figure 2 displays the experimental test site with the position of the GCPs.

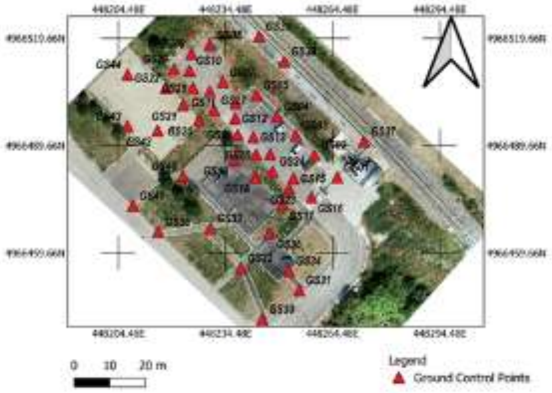

Figure 2 - Study area with the position of GCPs

3.2. Data Acqusition

In this research, the data collection process was carried out using a DJI Phantom 4 Pro [8]. The choice of the Phantom 4 Pro was deliberate, as it offered a powerful platform with remarkable imaging capabilities. Equipped with a one-inch, 20-megapixel CMOS sensor, this UAV was well-suited for capturing high-resolution imagery.

For flight planning, the commercial software application Litchi was used, and the internal camera settings were adjusted using the DJI GO app.

The flight height was consistent at 40 meters above the surface, unsuring that every image covered a surface of 60.19×40.13 m^2. This led to a GSD equal to 1.1 cm per pixel. The data acquisition took place in August, 2022.

Table 1 summarizes the main characteristics of the flight plan, as well as the exposure settings used during the UAV photogrammetric survey.

Table 1. Flight Plan Parameters with Exposure Settings

Parameter	Vrednost	Merna jedinica
Focal Length	8.8 24 (35mm format)	mm
Sensor size	13.2 (W) 8.8 (H)	mm mm
Sensor resolution	20	mpix
Image Resolution	5472 (W) 3648 (H)	pix pix
ISO Sensitivity	200	ISO
Flight height	40	m
Along-track Overlap	81	%
Cross-track Overlap	81	%
Exposure Time	1/1100	s
Ground Sample Distance	1.1	cm
Flight Speed	2.8	m/s

Before the UAV flight, 44 targets were uniformly positioned throughout the study area.

For this study, a precise GCP network was established through advanced GNSS technology. This method ensured uniform precision, underpinning accurate georeferencing crucial for robust and reliable data analyses.

The GCPs network was developed in order to establish a consistent spatial reference system for the territory covered by the study site. In UAV-SfM photogrammetry, ground control points are placed along the perimeter of the project area and along profiles perpendicular to the flight direction of the image sequences.

The network of GCPs included 44 points that were observed, as shown in Figure 2. The coordinates of the GCPs were obtained using the RTK GNSS method, relying on the active network of GNSS permanent stations called AGROS (Active Geodetic Reference Network of Serbia).

The GNSS receiver used (Leica GS18) was positioned centrally above each ground control point during the observations, and signal reception was conducted in three independent sessions, each lasting 30 seconds.

3.3 Data Processing

An algorithm based on SfM-MVS techniques was used to do the photogrammetric process. The workflow is divided into three steps. The software system initially identifies common points, often referred to as key points, among the provided photos to align them using a matching process. If two unique key points from separate images coincide, they are considered matching points. Utilizing these matching points, combined with the approximate image positions automatically extracted from the EXIF metadata, the software can execute a bundle adjustment, enabling the determination of the 3D coordinates for each point. [10].

In this study, three software systems were used to process the collected UAV photogrammetry images: Pix4D Mapper, Agisoft Metashape, and Trimble Inpho UASMaster.

The workflow in used software systems is described is as outlined below [9]:

- Image feature extraction and matching. Regardless of image scale or perspective, the software recognizes many noticeable spots in each image, and comparable feature points are recognized in several images. [11];
- Iterative bundle adjustment. The goal of BA is to detect the internal and exterior orientation elements of images by reducing the reprojection errors between predicted and observed locations, which can be translated into a nonlinear least-squares problem. [12];
- Model optimization based on control points. Control points offer supplementary external data regarding the geometry of the reconstructed scene. The optimization process in the utilized software refines camera positions and diminishes non-linear project distortions by integrating ground control points.[13].
- Point cloud density matching. The MVS image matching algorithm functions at a pixel-level scale in the image, constructing dense clouds and significantly enhancing the point density by several orders of magnitude.;
- Generate digital surface model and orthomosaic.

3.4. Ground Control Points

During the design of the GCP network to materialize a unified reference system, special attention was given to the selection and arrangement of the GCPs.The project included GCPs distributed along the perimeter of the block, which is crucial for propagating positional errors within the block.

Additionally, positions for ground control points within the block were also planned to achieve a proper distribution, which is essential for propagating vertical errors within the block.

To evaluate how the quantity of GCPs impacts the positional and vertical accuracy of UAV photogrammetric products, six different configurations (scenarios) were established.

These configurations were labeled as Scenario S-I, Scenario S–II, Scenario S-III, Scenario S-IV, Scenario S-V and Scenario S-VI.

The first scenario (S-I) consists of six evenly distributed GCPs, with five located along the perimeter of the experimental site and one in the center (Figure 3).

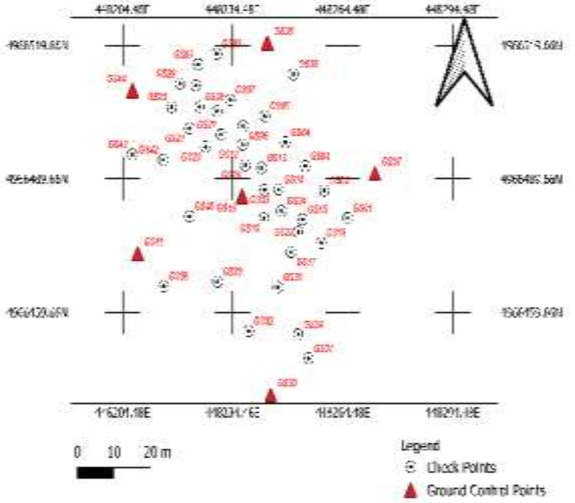

Figure 3 - GCPs Configuration in Scenario S-I (6 GCPs)

In all other scenarios, an increase in the quantity of GCPs was implemented both along the perimeter and inside the site to attain a more consistent and uniform distribution. In these scenarios, the maximum number of GCPs is 21.

Each configuration had a specific number of GCPs, as follows:

- Scenario S-I: 6 GCPs and 38 CPs;
- Scenario S-II: 9 GCPs and 35 CPs (3 additional GCPS added to the 6 GCPs from Scenario S-I);
- Scenario S-III: 12 GCPs and 32 CPs (3 additional GCPS added to the 9 GCPs from Scenario S-II);
- Scenario S-IV: 15 GCPs and 29 CPs (3 additional GCPS added to the 12 GCPs from Scenario S-III);
- Scenario S-V: 18 GCPs and 26 CPs (3 additional GCPS added to the 15 GCPs from Scenario S-IV), and
- Scenario S-VI: 21 GCPs and 23 CPs(3 additional GCPS added to the 18 GCPs from Scenario S-V).

For each configuration, the GCPs were spatially distributed across the survey area in a manner that ensured proper coverage and representation of the terrain.

Careful consideration was given to the geographic distribution of GCPs to capture variations in topography and land features.

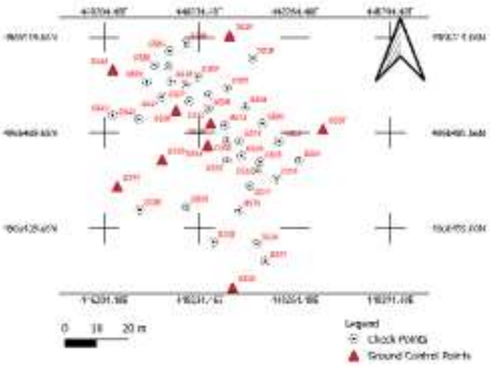

Figure 4 - GCPs Configuration in Scenario S-II (9 GCPs)

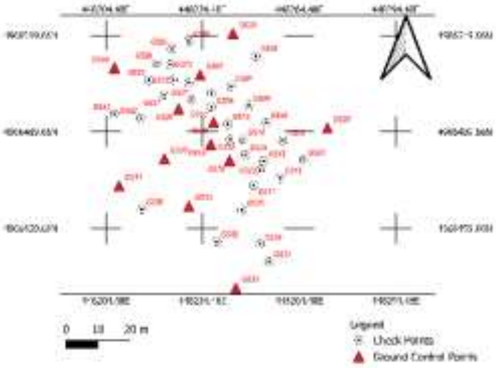

Figure 5 - GCPs Configuration in Scenario S-III (12 GCPs)

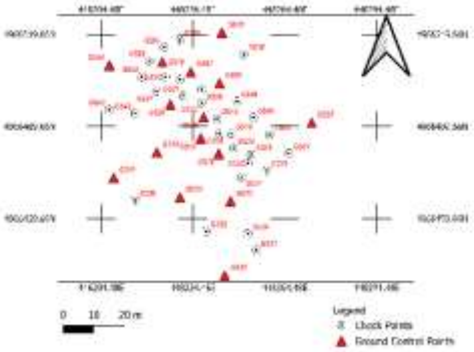

Figure 6 - GCPs Configuration in Scenario S-IV (15 GCPs)

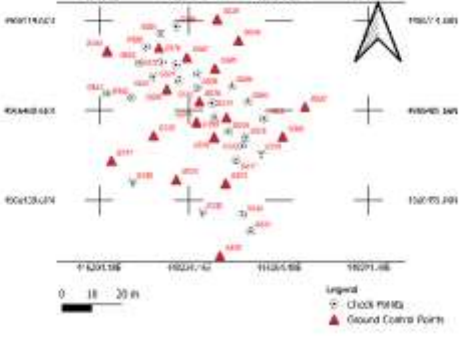

Figure 7 - GCPs Configuration in Scenario S-V (18 GCPs)

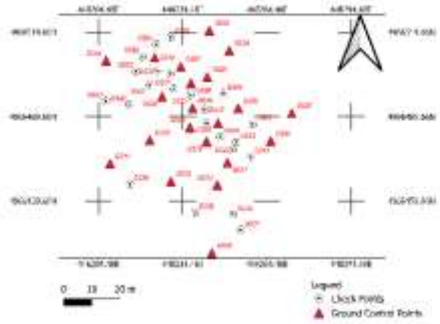

Figure 8 - GCPs Configuration in Scenario S-VI (21 GCPs)

3.5. Accuracy Assessment

To evaluate the geometric accuracy of generated UAV photogrammetric models, the quality of geometry is assessed using statistical measures such as the RMSE values. The software systems used in the block aerial triangulation provide information on the RMSE values of the variance on the GCPs and CPs, including:

$$RMSE_X = \sqrt{\frac{\sum_{i=1}^{n}(X_{UAV} - X_{GNSS})^2}{n}} \tag{1}$$

$$RMSE_Y = \sqrt{\frac{\sum_{i=1}^{n}(Y_{UAV} - Y_{GNSS})^2}{n}} \tag{2}$$

$$RMSE_Z = \sqrt{\frac{\sum_{i=1}^{n}(Z_{UAV} - Z_{GNSS})^2}{n}} \tag{3}$$

$$RMSE_R = \sqrt{RMSE_X^2 + RMSE_Y^2}\,, \tag{4}$$

where $X_{UAV}, Y_{UAV}, Z_{UAV}$) are the coordinates of points obtained by processing the formed UAV photogrammetric blocks, and ($X_{GNSS}, Y_{GNSS}, Z_{GNSS}$) are the coordinates of points obtained by the RTK GNSS method, and n represents the overall count of reference points used for comparison [14].

Errors arising from disparities between the reconstructed model and in-situ coordinates are termed as errors. The impact of each error on the RMSE is directly proportional to the square of the amount of the error. Consequently, RMSE is highly responsive to estimated outlier values, as substantial errors exert a significant influence on RMSE values. Therefore, it is advisable to study the value of the error for each CP to check whether it is an outlier and, if so, to try to find the cause [10].

4. RESULTS

4.1. Model Evaluation Based on RMSE

The input parameters for the formation of UAV photogrammetric image blocks, as well as their subsequent processing in the software solutions Pix4D Mapper, Agisoft Metashape, and Trimble Inpho UAS-Master, include: 146 images with a resolution of 5.472x3.648 pixels and an approximate ground sample distance of 1.1cm/pix. The along and cross-track image overlap is 81% each.

Coordinates of 44 GCPs in the State Coordinate System of the Republic of Serbia.

Using the extracted coordinates from the generated models and the in-situ coordinates of Ground Control Points (GCPs) and Check Points (CPs), the vertical and horizontal Root Mean Square Errors for each scenario were computed via Equations (1) to (4).

For each defined configuration of GCPs, RMSE values of positional and vertical deviations on GCPs and ChPs were calculated. The obtained RMSE values of positional and vertical deviations on GCPs and ChPs are presented in the corresponding graphs.

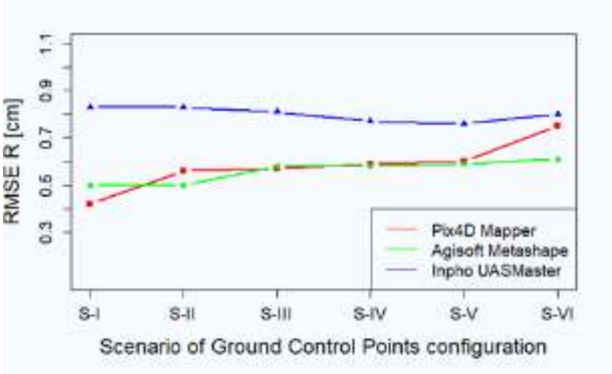

Figure 9 - RMSE values of positional deviation on GCPs in the UAV photogrammetric block formed by the SfM approach for all three used software systems

There is no significant change in the RMSE values of positional deviation on the GCPs when the quantity of GCPs increases for all three software systems used, from sparser to denser configurations (Figure 9).

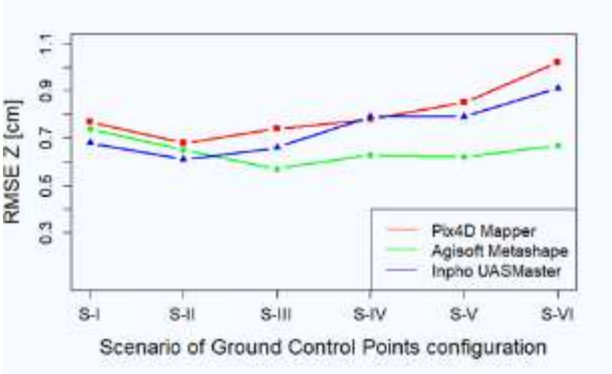

Figure 10 - RMSE values of elevation deviation on GCPs in the UAV photogrammetric block formed by the SfM approach for all three used software systems

The RMSE values of the vertical deviation on the ground control points for the Agisoft Metashape software system are identical for each scenario of GCPs. However, using the Pix4D Mapper and Inpho UASMaster software systems, there is an increase in the RMSE values of the vertical deviation on the control points in scenarios S-IV, S-V, and S-VI (Figure 10). In certain instances where the quantity of GCPs was heightened, an increase in RMSE occurred, possibly attributed to errors introduced during the in-situ measurement of the additional GCPs.

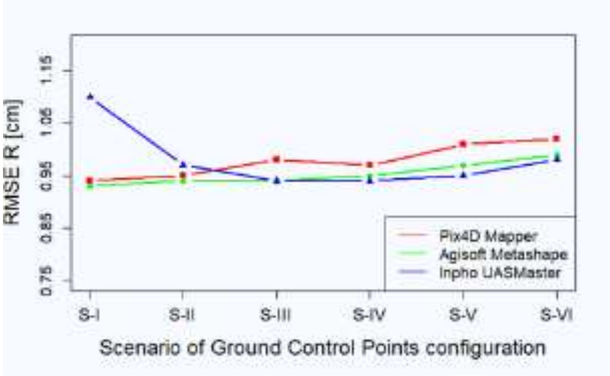

Figure 11 - RMSE values of positional deviation on CPs in the UAV photogrammetric block formed by the SfM approach for all three used software systems

The RMSE values of the positional deviation on the CPs obtained using all three software systems are identical across all six scenarios (Figure 11).

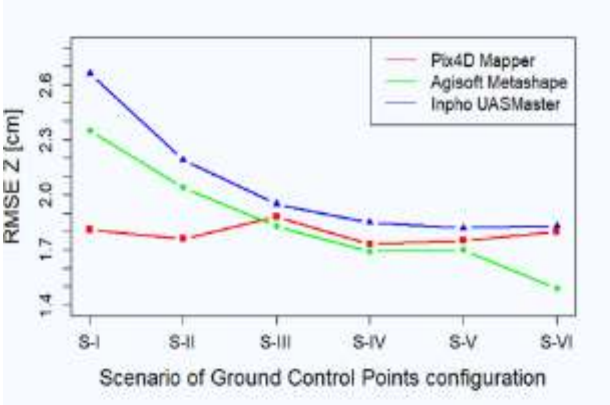

Figure 12 - RMSE values of elevation deviation on CPs in the UAV photogrammetric block formed by the SfM approach for all three used software systems

A noticeable trend of decreasing RMSE values of the vertical deviation on the CPs can be observed as the quantity of GCPs increases for the Agisoft Metashape and Inpho UASMaster software systems (Figure 12).

The RMSE values of vertical deviation on the check points for all three used software systems converged to approximately twice the value of the average spatial resolution (Figure 12). Additionally, the RMSE values of positional deviation on GCPs converged to the value of the average spatial resolution (Figure 11).

The findings of this research align with the conclusion that augmenting the quantity of Ground Control Points used in the BA leads to increased altimetric accuracy, independent of the spatial distribution. In all the generated models, the values obtained for altimetric accuracy (RMSE$_Z$) surpass those acquired for planimetric accuracy (RMSE$_R$). The RMSE values of positional deviation on Check Points also converge to the value of the average spatial resolution. This implies that using more GCPs helps to achieve higher positional accuracy in the photogrammetric products across all three software systems.

4.2. Assessment of camera calibration parameter stability

Table 2 presents the estimated values of the interior orientation elements using the Pix4D Mapper software system, while Table 3 provides the estimated values using the Agisoft Metashape software system, and Table 4 provides the estimated values using the Inpho UASMaster software system. It can be noted that augmenting the number of orientation points in data processing through the employed software systems does not lead to notable alterations in the derived interior orientation values. When comparing these values among the software systems, disparities in the estimated interior orientation parameters become apparent.

Table 2. Evaluation of interior orientation elements - software system: Pix4D Mapper

Scenario	*C(mm)*	*ξ0(mm)*	*η0(mm)*
S – I	8.547	6.407	4.313
S – II	8.549	6.407	4.312
S – III	8.549	6.407	4.311
S - IV	8.551	6.407	4.310
S-V	8.551	6.407	4.310
S-VI	8.552	6.407	4.310

Table 3. Evaluation of interior orientation elements - software system: Agisoft Metashape

Scenario	C(тт)	ξ0(тт)	η0(тт)
S – I	8.547	6.411	4.316
S – II	8.549	6.411	4.316
S – III	8.550	6.411	4.315
S - IV	8.551	6.411	4.315
S-V	8.552	6.411	4.314
S-VI	8.552	6.411	4.314

The obtained estimated values of the interior parameters, due to the absence of significant changes in their values, can be used as fixed camera parameter values in future UAV photogrammetric projects, but only within the software system through which these parameters were estimated.

Table 4. Evaluation of interior orientation elements - software system: Inpho UASMaster

Scenario	C (тт)	ξ0(тт)	η0(тт)
S – I	8.550	6.410	4.313
S – II	8.554	6.410	4.311
S – III	8.555	6.410	4.311
S - IV	8.555	6.410	4.310
S-V	8.557	6.410	4.309
S-VI	8.557	6.410	4.309

Within Table 5, Table 6, and Table 7, the values of estimated parameters for radial and decentering sensor distortions obtained using the employed software systems are presented. The utilized software systems employ the "pinhole" mathematical model for the camera's interior orientation according to Brown's distortion model [15].

Table 5. Parameters of radial and decentering distortion for different configurations of ground control points - software system: Pix4D Mapper

	Scenario					
	S-I	S-II	S-III	S-IV	S-V	S-VI
k1*104 (mm)	22.6	23.6	24.3	24.6	25.7	25.4
k2*103 (mm)	-13.7	-13.7	-13.7	-13.7	-13.9	-13.8
k3*103 (mm)	12.1	12.1	12.1	12.2	12.8	12.2
p1*104 (mm)	-10.5	-10.7	-10.9	-11	-11.1	11.2
p2*105 (mm)	-63.9	-64	-63.7	-63.7	-63.5	-63.4

Table 6. Parameters of radial and decentering distortion for different configurations of ground control point – software system Agisoft Metashape

	Scenario					
	S-I	S-II	S-III	S-IV	S-V	S-VI
k_1*10^4 *(mm)*	28.8	29.8	30.6	30.9	31.6	31.8
k_2*10^3 *(mm)*	-17.6	-17.7	-17.7	-17.7	-17.8	-17.8
k_3*10^3 *(mm)*	15.8	15.8	15.9	15.9	15.9	15.9
p_1*10^5 *(mm)*	-56.8	-56.7	-56.6	-56.6	-56.6	-56.5
p_2*10^5 *(mm)*	-90.8	-93.2	-94.9	-95.7	-97.1	-97.6

Table 7. Parameters of radial and decentering distortion for different configurations of ground control points – software system Inpho UASMaster

	Scenario					
	S-I	S-II	S-III	S-IV	S-V	S-VI
k_1*10^4 *(mm)*	2.47	2.72	2.78	2.86	2.97	2.97
k_2*10^6 *(mm)*	-2.38	-2.40	-2.37	-2.40	-2.41	-2.41
k_3*10^8 *(mm)*	2.89	2.91	2.91	2.92	2.93	2.93
p_1*10^4 *(mm)*	1.14	1.19	1.20	1.22	1.24	1.24
p_2*10^5 *(mm)*	6.26	6.24	6.24	6.23	6.22	6.22

5. DISCUSION

Numerous research studies have investigated the most suitable Ground Control Point density for UAV photogrammetry. However, certain locations may present challenging or inaccessible terrains, making it demanding or even impossible for land surveyors to physically access the site. In such scenarios, the use of UAV photogrammetry becomes essential to obtain accurate and comprehensive data.

Empirically, it has been determined that the positional accuracy of UAV-SfM photogrammetry is approximately equal to the spatial resolution, while the vertical accuracy is twice the value of the same resolution [5]. Taking into account the spatial resolution of the collected images, which is 1.1cm/pix, it can be concluded that the achieved results are satisfactory in terms of accuracy.

The results of the research conducted by Bursać et al. in [3], Harwin et al. in [4], and Sanz-Ablanedo et al. in [5] show that augmenting the quantity of GCPs leads to a decrease in RMSE values of vertical deviation on both GCPs and CPs. By analyzing the outcomes of this research, it is possible to infer that the results obtained are consistent with the findings of the previously stated articles.

Augmenting the quantity of GCPs has a minimal impact on the RMSE values of positional deviation, affirming the model's reliability.

The six scenarios exhibit satisfactory accuracies, falling within the range of 0.7 – 1.1 GSD in planimetry and 1.5 – 2.7 GSD in altimetry [16]. This achievement is attributed to the high-quality in-situ data, along with effective planning and processing strategies.

Based on the analysis of RMSE values of vertical deviation on GCPs and CPs, it can be concluded that special attention should be given to the quantity and distribution of GCPs involved in the SfM block-aerotriangulation process. Increasing the number of GCPs contributes to reducing the RMSE values of deviation on GCPs, but it is necessary to determine their optimal number to avoid overfitting issues.

The optimal number of GCPs for the experimental site is 12, according to the analysis of RMSE values for positional and vertical deviation on GCPs and CPs. Adding more control points than this number did not significantly improve positional accuracy, and in some cases, it increased vertical deviation due to potential errors introduced during ground measurements of newly added GCPs. Furthermore, adopting a denser GCPs configuration would be impracticable and unneeded for the photogrammetric tasks carried out in this study because doing so would result in increased time and price without producing equivalent advantages in accuracy.

The coordinates of GCPs, used as input values in the SfM block-aerotriangulation process, represent a potential source of errors. It is questionable whether the implemented SfM approaches in the used software systems are robust enough to handle the influence of gross errors in the coordinates of GCPs on the final results and whether they are capable of detecting them.

6. CONCLUSION AND RECOMMENDATIONS

The assessment of the quality of product geometry in UAV photogrammetry is crucial to guarantee the reliableness and accuracy of the obtained results. The number of GCPs employed in the block aerotriangulation process has a major impact on photogrammetric product accuracy. Insufficient use of GCPs can lead to inadequate geometric accuracy of the resulting products and may introduce systematic errors such as model deformation, among others.

This study's findings illustrate the correlation between the accuracy of UAV photogrammetry and the number of GCPs employed in the block aerotriangulation. The research results are summarized as follows:

In the sparsest configuration, consisting of 6 GCPs, the RMSE values of vertical deviation on control points for the Pix4D Mapper and Inpho UASMaster software systems were approximately 2.5 times the spatial resolution. By augmenting the quantity of GCPs in the block aerotriangulation process, the RMSE values of vertical deviation converged to twice the spatial resolution, which has also been demonstrated in other research studies.

By analyzing the data available in the form of a correlation matrix provided in the report on block aerotriangulation using SfM approach generated by the employed software systems, it can be concluded that the parameters of inexpensive, non-metric cameras in the internal orientation are highly correlated with each other, indicating the instability of the internal geometry. There are no significant differences in the values of the internal orientation parameters and camera calibration parameters estimated through the self-calibration process using all three used software systems.

Several recommendations for further research are proposed to offer deeper insights into the impact of the quantity and distribution of control points on the accuracy of block aerotriangulation using the SfM approach. The first suggestion is to expand the coverage area of the experimental site to a larger workspace. Additionally, the research can be extended to investigate the factors related to the quality of images (radiometric and geometric) and flight planning (flight height, overlap of images, and geometry of the photogrammetric block) and their impact on the accuracy of the process.

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REZIME

ISPITIVANJE UTICAJA BROJA ORIJENTACIONIH TAČAKA NA GEOMETRIJSKU TAČNOST UAV FOTOGRAMETRIJSKIH PROIZVODA FORMIRANIH POMOĆU PRISTUPA STRUKTURE IZ POKRETA

Položajna i visinska tačnost fotogrametrijskih proizvoda nastalih obradom UAV aerofotogrametrijskih snimaka pomoću SfM (engl. Structure from Motion) pristupa zavisi od nekoliko faktora, uključujući parametre plana leta, kvalitet kamere, kalibracije kamere, korišćenog SfM algoritma i postupka geo-referenciranja. U radu je analiziran uticaj broja orijentacionih tačaka na kvalitet geometrije formiranih modela i stabilnost parametara kalibracije kamere ocenjenih kroz postupak blok-aerotriangulacije sa samokalibracijom (engl. self-calibration). Obrada prikupljenih UAV fotogrametrijskih snimaka izvršena je pomoću tri softverska sistema: Pix4D Mapper, Agisoft Metashape i Trimble Inpho UASMaster. Preciznost blok-aerotriangulacije je evaluirana korišćenjem standardnih statističkih ocena kvaliteta. Rezultati istraživanja pokazuju da povećanje broja orijentacionih tačaka doprinosi pouzdanosti modela i smanjenju RMSE vrednosti visinskog odstupanja na kontrolnim tačkama. RMSE vrednosti visinskog odstupanja za sva tri korišćena softverska sistema konvergirale su, približno, ka dvostrukoj vrednosti prosečne prostorne rezolucije. Takođe, RMSE vrednosti položajnog odstupanja na orijentacionim tačkama konvergirale su ka vrednosti prosečne prostorne rezolucije.

Ključne reči: *UAV fotogrametrija, Structure-from-Motion, orijentacione i kontrolne tačke, blok-aerotriangulacija*