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Research Article

Accuracy Analysis of Photogrammetric Digital Topographic Map Production: The Case Study of Kuruca Village in Bingöl Center

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Abstract: This study examines the accuracy analysis of digital maps produced through photogrammetric methods. With the advancements in geographic information systems (GIS) and remote sensing technologies, the factors influencing the accuracy of photogrammetric maps and the methods to enhance this accuracy have gained significant importance. The research investigates the impact of factors such as the quality of the equipment used, the distribution of ground control points (GCPs), environmental conditions, and the integration of modern technologies (e.g., UAVs, kinematic GPS, LiDAR) on map accuracy. Drawing on various studies in the literature, the advantages of UAV photogrammetry in challenging terrain, its cost-effectiveness, and data collection efficiency are highlighted. Additionally, the effects of focal length, the distribution of control points, and the software utilized on accuracy are comprehensively discussed. The study emphasizes the importance of steps such as reconnaissance, flight planning, and data processing in the production process of photogrammetric maps. Accuracy analysis evaluates horizontal and vertical deviations to determine the compliance of maps with standards and their capacity to meet user needs. The findings underscore that the accuracy analysis of photogrammetric methods is critical for the reliability and currency of maps. The integration of modern technologies and the development of new methodologies are highlighted as means to enhance the precision and efficiency of photogrammetric mapping processes. Accordingly, this study advocates for continued research aimed at improving the accuracy of photogrammetric maps.

Keywords: Photogrammetry; Digital Topographic Maps; Accuracy Analysis; Unmanned Aerial Vehicles.

1. Introduction

The accuracy analysis of photogrammetric digital base map production has gained increasing importance with the advancements in Geographic Information Systems (GIS), remote sensing, and digital mapping technologies. These developments have made photogrammetric methods not only a subject of academic research but also a critical tool in engineering projects, land management, environmental planning, and infrastructure development. Accuracy analysis is a key component in determining whether the produced maps meet standards, fulfill user requirements, and ensure reliability in engineering applications.

Photogrammetric methods stand out for their high accuracy, cost efficiency, and speed, particularly in large-scale mapping projects. However, the accuracy of these methods is influenced by several factors, including the quality of equipment, the distribution of ground control points (GCPs), environmental conditions, data collection techniques, and the integration of modern technologies. Emerging technologies such as unmanned aerial vehicles (UAVs), LiDAR, kinematic GPS/IMU, and advanced software play a significant role in enhancing accuracy (Arslan & Yağcıoğlu, 2021; Yiğit et al., 2023).

In recent years, UAV photogrammetry has been extensively studied in the literature due to its cost efficiency, ease of use, and high accuracy potential. This method significantly facilitates and accelerates data collection processes in challenging terrains and inaccessible regions. The study by Yiğit et al. highlighted the advantages of UAV photogrammetry in open-pit mining, emphasizing its contributions to rapid data collection, precise measurements, and cost reduction (Yiğit et al., 2023). Additionally, research by Hastaoğlu et al. demonstrated that variations in focal lengths in UAV photogrammetry could significantly impact accuracy, highlighting the importance of these parameters in achieving precise results (Hastaoğlu et al., 2021; Günal et al., 2021).

Moreover, photogrammetric mapping methods conducted with mobile devices and portable equipment have become an increasingly prominent research topic. In Öcalan's study, the accuracy analysis of 3D point clouds obtained from the cameras and LiDAR sensors of smartphones and tablets revealed their potential to improve accessibility while offering notable advantages in accuracy (Öcalan, 2024). Such innovative approaches make photogrammetric mapping processes more inclusive and accessible to a broader user base.

Another critical factor affecting the accuracy of photogrammetric methods is the distribution and number of ground control points. Bekçi and Kuşak’s research compared the photogrammetric data generated by UAVs with ground-based surveying methods, revealing comparable levels of accuracy between the two techniques (Bekçi & Kuşak, 2022). Furthermore, the work by Eroğlu and Narin provided significant insights into the performance differences between UAV-generated digital elevation models (DEMs) and traditional methods, emphasizing the importance of accuracy in this domain (Eroğlu & Narin, 2021).

The integration of technological innovations into photogrammetric methods has added complexity and depth to accuracy analyses. For instance, Karslı et al. developed strategies to enhance accuracy by employing image matching and LiDAR-based point clouds for automated building extraction (Karslı et al., 2022). Such studies contribute to obtaining photogrammetric products with higher precision, driving the dynamic evolution of the field.

This study aims to examine the factors influencing the accuracy of photogrammetric digital map production and propose strategies for improvement, focusing on the case of Kuruca Village in Bingöl. By analyzing findings obtained from a local-scale application, this research emphasizes the theoretical and practical importance of photogrammetric methods and seeks to contribute to the existing literature in this field.

2. Study area

The study area is located in Kuruca Village, which lies within the central district of Bingöl Province. This region spans an area of approximately 35 hectares, characterized by diverse topographical features and a mix of natural and rural landscapes. Kuruca Village is situated roughly 30 kilometers west of Bingöl city center, making it easily accessible via regional road networks.

The area is notable for its geographical setting, encompassing a variety of landforms and vegetation types, which provide an ideal setting for photogrammetric mapping and accuracy analysis. The choice of this location is also influenced by its representative nature, as it reflects typical rural settlement patterns and environmental conditions commonly found in the region. This combination of accessibility and representativeness makes Kuruca Village a valuable case study for exploring the application of modern photogrammetric methods.

3. Geodetic Studies

In this section, the geodetic studies conducted for the successful execution of the photogrammetric mapping process are detailed, highlighting the key activities such as reconnaissance, establishment of control points, and the methods used to ensure the accuracy of the measurements.

3.1. Reconnaissance and establishment

The project boundary area of Kuruca Village is shown in Figure 1. The primary objective of the reconnaissance phase was to conduct a thorough survey and establish a reliable geodetic framework for the photogrammetric mapping process. To achieve this, it was essential to perform an aerial triangulation adjustment and develop a local geoid reference point network. The locations for the triangulation points were carefully selected to cover the entire project area while maintaining optimal spatial distribution across the site. The placement of these points was executed with great attention to detail, ensuring that they were placed in locations that would allow for clear visibility in aerial photographs, easy access for fieldwork, and safety from factors that could interfere with GNSS signal reception, such as tall structures or dense vegetation.

The triangulation points were positioned on stable, solid ground, selected to minimize the risk of future displacement or ground instability, thus guaranteeing the long-term reliability of the measurements. Furthermore, particular consideration was given to ensuring that these points would remain unaffected by potential changes in environmental conditions, such as flooding or erosion, which could potentially disrupt the accuracy of the measurements over time.

The establishment and marking of the triangulation points were carried out in accordance with the Ministry of Public Works and Settlement's General Directorate of Mapping Standards for Map and Cadastre Studies (BÖHHBÜY), which outlines the required procedures and specifications for geodetic surveys. These standards ensured that all aspects of the process, including the precise marking and recording of the triangulation points, followed the established technical guidelines to guarantee the accuracy of the final geodetic data.

In total, six ground control points (GCPs) were identified across the study area. These points were carefully selected to represent key locations within the project boundary, ensuring that they were evenly distributed and strategically placed to cover both the central and peripheral areas of the region. To verify the accuracy of the coordinates of the GCPs, the Real-Time Kinematic (RTK) method was employed, utilizing single-point checks to assess the positional accuracy of the points. RTK measurements, with their high precision, allowed for real-time corrections, ensuring that any potential errors in positioning were immediately identified and rectified.

In addition to their role in triangulation, the geodetic markers were also used as leveling points. The elevations of these points were measured with great precision through detailed leveling surveys, contributing to the vertical accuracy of the photogrammetric data. This dual functionality of the geodetic points—serving both as horizontal and vertical reference markers—proved invaluable for the overall accuracy of the photogrammetric mapping process. The integration of these leveling points also ensured that the produced maps would meet the necessary topographic and elevation standards.

Throughout the reconnaissance and establishment phase, particular emphasis was placed on selecting optimal locations for all control points, carefully considering environmental factors, accessibility, and long-term stability. This comprehensive approach ensured the development of a robust geodetic framework that would support accurate and reliable data collection throughout the project. The careful planning and execution of this phase played a critical role in ensuring the success of the entire study and laid the foundation for the accuracy and precision of the final photogrammetric products.

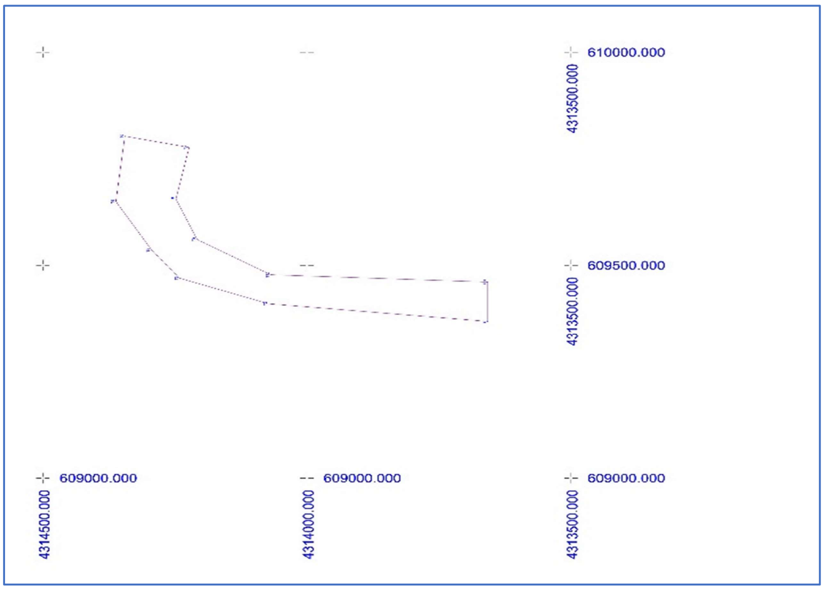

Figure 1. Project boundary area.

4. Photogrammetric Studies

In order to produce accurate and reliable digital base maps, photogrammetric techniques are employed, involving several critical steps from planning to data collection and processing. Among these steps, flight planning and execution stand out as fundamental stages that directly influence the quality and precision of the final map products.

4.1. Flight planning process

The flight planning process begins with a thorough analysis of the mapping area. The geographic extent, topographical features, and any environmental constraints of the area must be carefully evaluated. These considerations will influence various aspects of the planning, including the selection of flight altitude, the type of sensors to be used, and the overall methodology for data acquisition. It is essential to select the appropriate flight parameters that best suit the specific characteristics of the terrain being mapped, as different areas may require different approaches based on factors such as slope, vegetation cover, and land use.

A key aspect of this phase is determining the placement of ground control points (GCPs). These reference points are critical for georeferencing the photogrammetric images, ensuring that the data collected corresponds accurately to real-world coordinates. The positioning of these points must be carefully planned to achieve optimal distribution across the project area, taking into account factors such as accessibility, visibility, and the terrain's topography. The GCPs serve as the foundation for the subsequent georeferencing process, which aligns the collected images to known spatial coordinates, ensuring the accuracy and reliability of the photogrammetric products.

Another crucial element of flight planning involves the optimization of image overlap. The overlap between images plays a significant role in generating accurate three-dimensional models from the captured images. To ensure this accuracy, longitudinal overlap (along the flight path) and lateral overlap (between adjacent flight strips) must be carefully calibrated. Longitudinal overlap is typically recommended to fall between 60% and 80%, while lateral overlap should range from 30% to 60%. These overlaps are essential for the stereoscopic pairing of images, which facilitates the generation of accurate 3D models and ensures proper spatial coordination of the data.

Execution of the Flight: The execution phase involves the actual flight and data collection. This phase requires meticulous attention to detail, as any discrepancies in the flight execution can result in errors in the collected data. A major consideration during this phase is the weather conditions. Favorable weather is crucial for ensuring the high quality of the images captured during the flight. Factors such as wind speed, cloud cover, temperature, and light conditions can affect image clarity, which in turn can compromise the accuracy of the photogrammetric data. Additionally, the presence of strong winds or turbulence can cause instability in the UAV or aircraft, further affecting the precision of the flight path and sensor readings.

The selection and calibration of the sensors used in the flight are equally important. UAVs or aircraft equipped with photogrammetric cameras must undergo thorough calibration to ensure that the captured images reflect true spatial relationships. Errors in sensor calibration can lead to inaccuracies in the final data. Therefore, prior to data collection, it is essential to verify the performance of all sensors and ensure they are properly calibrated. Furthermore, the integration of high-precision GPS systems and inertial navigation units (INU) during the flight enhances the positional accuracy of the captured data. These technologies enable real-time tracking of the flight platform's position, ensuring that each image is correctly georeferenced in relation to the project's coordinate system.

Additionally, the use of real-time kinematic (RTK) GPS systems allows for continuous, high-precision positioning throughout the flight. This system provides real-time corrections for positional data, improving the accuracy of the images captured, especially in areas where traditional GPS may struggle with signal reception. The use of RTK systems significantly reduces the potential for errors in the georeferencing process, making it an indispensable tool in modern photogrammetric workflows.

Impact of Flight Conditions and Post-Processing: Once the flight is completed and the images are captured, the post-processing phase begins. The images are then analyzed and processed to generate the photogrammetric products, such as orthophotos, digital surface models (DSMs), and 3D models. However, the quality and accuracy of the final products are highly dependent on the conditions during the flight. If any issues arise during data collection—such as poor calibration, inadequate image overlap, or adverse weather conditions—the post-processing phase may become more complex, requiring additional corrections and adjustments.

Ultimately, the flight planning and execution stages are foundational to the success of any photogrammetric mapping project. Proper planning, attention to detail during the flight, and the use of high-precision technology all contribute to the creation of accurate and reliable photogrammetric maps. Any oversight in these critical stages can introduce errors into the final product, undermining the effectiveness of the mapping process. Thus, careful attention to every aspect of the flight planning and execution stages is essential for the production of high-quality, accurate digital base maps.

In order to produce accurate and reliable digital base maps, photogrammetric techniques are employed, involving several critical steps from planning to data collection and processing. Among these steps, flight planning and execution stand out as fundamental stages that directly influence the quality and precision of the final map products.

Figure 2 presents the flight plan for Kuruca Village, depicted on a Google Earth image. This plan outlines the coverage area and provides essential information regarding the flight paths to be followed during data collection.

Figure 2. Kuruca Village measurement area flight plan Google Earth image.

Figure 3 showcases the screen of the *PIX4D* program used during the adjustment process. *PIX4D* is a photogrammetric software suite that facilitates the processing of images into high-quality geospatial data. Its use was essential for obtaining accurate three-dimensional models and maps from the aerial images.

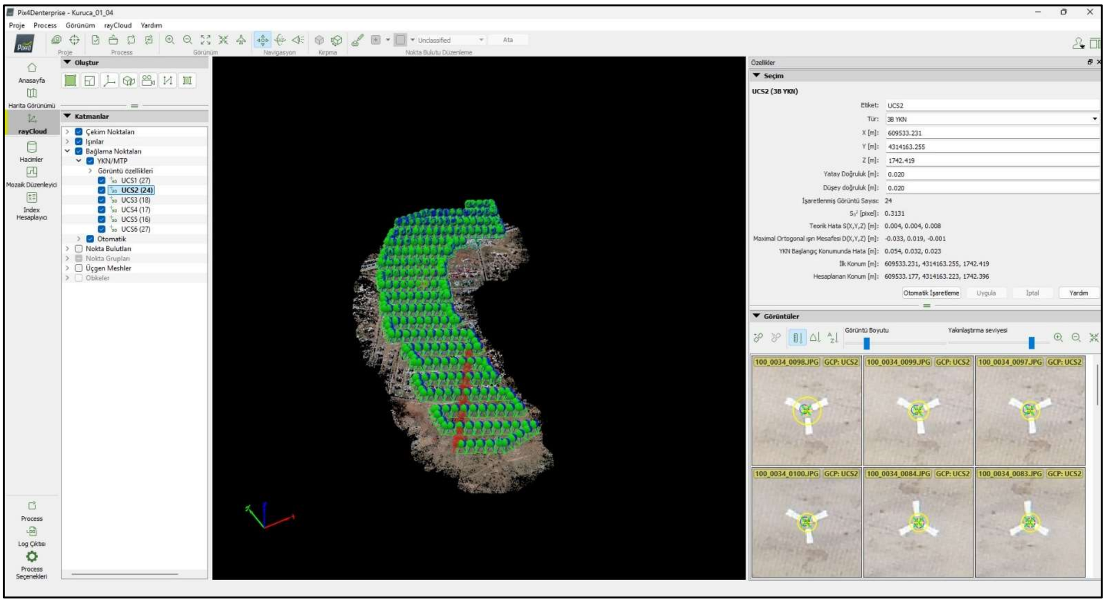

Figure 3. Screenshot of PIX4D programme used during balancing.

Figure 4 presents the Kuruca Project's leveling data, which was crucial for the geometric accuracy of the photogrammetric work. The project, labelled as Kuruca_01_04, was processed on April 1, 2024, at 16:55:17. The dataset utilized an FC6310R camera with an 8.8 mm focal length and a resolution of 5472x3648 pixels (RGB). Key metrics from the photogrammetric processing include:

- Average Ground Sampling Distance (GSD): 2.99 cm (1.18 in), indicating high-resolution outputs.

- Area Covered: 0.357 km² (35.7499 ha / 0.14 sq. mi. / 88.3855 acres).
- Initial Processing Time (without report): 14 minutes and 59 seconds.

Quality Assessment

- Image Keypoints: A median of 44,686 keypoints was detected per image, signifying sufficient detail for robust feature extraction.
- Dataset Calibration: All 268 images were successfully calibrated (100%), with only 15 images excluded.
- Camera Optimization: The relative difference between the initial and optimized camera internal parameters was 0.35%, reflecting excellent calibration accuracy.
- Image Matching: The median number of matches per calibrated image was 23,438.4, demonstrating high consistency in image alignment.
- Georeferencing: Six Ground Control Points (GCPs) were utilized, achieving a mean Root Mean Square (RMS) error of 0.056 m, confirming the high geospatial accuracy of the dataset.

Summary

Project	Kuruca_01_04
Processed	2024-04-01 16:55:17
Camera Model Name(s)	FC6310R_8.8_5472x3648 (RGB)
Average Ground Sampling Distance (GSD)	2.99 cm / 1.18 in
Area Covered	0.357 km^2 / 35.7499 ha / 0.14 sq. mi. / 88.3855 acres
Time for Initial Processing (without report)	14m:59s

Quality Check

Images	median of 44686 keypoints per image	✓
Dataset	268 out of 268 images calibrated (100%), 15 images disabled	✓
Camera Optimization	0.35% relative difference between initial and optimized internal camera parameters	✓
Matching	median of 23438.4 matches per calibrated image	✓
Georeferencing	yes, 6 GCPs (6 3D), mean RMS error = 0.056 m	✓

Figure 4. Kuruca Village Project balancing data.

Figure 5 illustrates the elevation control point calculations, which were vital for ensuring the accuracy of height data in the project area. The precise measurement of these points allowed for the verification and correction of any discrepancies in the elevation values. Six GCPs, labeled UCS1 through UCS6, were used to ensure georeferencing accuracy. The following metrics summarize their performance:

- Positional Accuracy (XYZ): Each GCP was measured with a precision of 0.020 m.
- Error Analysis:
- Mean errors in X, Y, and Z directions were -0.000438 m, 0.000814 m, and -0.000319 m, respectively.
- The overall RMS error was 0.049693 m, confirming excellent alignment.
- Projection Errors: Projection errors ranged between 0.692 and 0.897 pixels, indicating accurate placement of GCPs in the photogrammetric model.
- Verification: All GCPs were verified, with a majority confirmed both automatically and manually.

Geolocation Details

Ground Control Points

GCP Name	Accuracy XY/Z [m]	Error X [m]	Error Y [m]	Error Z [m]	Projection Error [pixel]	Verified/Marked
UCS1 (3D)	0.020/ 0.020	0.057	0.009	-0.020	0.716	27 / 27
UCS2 (3D)	0.020/ 0.020	0.053	0.031	0.023	0.714	24 / 24
UCS3 (3D)	0.020/ 0.020	0.015	0.062	0.145	0.692	18 / 18
UCS4 (3D)	0.020/ 0.020	-0.052	-0.091	-0.033	0.819	17 / 17
UCS5 (3D)	0.020/ 0.020	-0.076	-0.029	-0.060	0.797	16 / 16
UCS6 (3D)	0.020/ 0.020	0.001	0.022	-0.056	0.897	27 / 27
Mean [m]		-0.000438	0.000814	-0.000319		
Sigma [m]		0.049693	0.049131	0.070492		
RMS Error [m]		0.049695	0.049138	0.070493		

Localisation accuracy per GCP and mean errors in the three coordinate directions. The last column counts the number of calibrated images where the GCP has been automatically verified vs. manually marked.

Figure 5. Ground control points calculations.

Figure 6 shows the screen of the *Vırtual Surveyor* program, which was used for the drawing phase of the project. The software's interface was instrumental in processing and analyzing the data acquired from the aerial survey, providing essential tools for geospatial analysis.

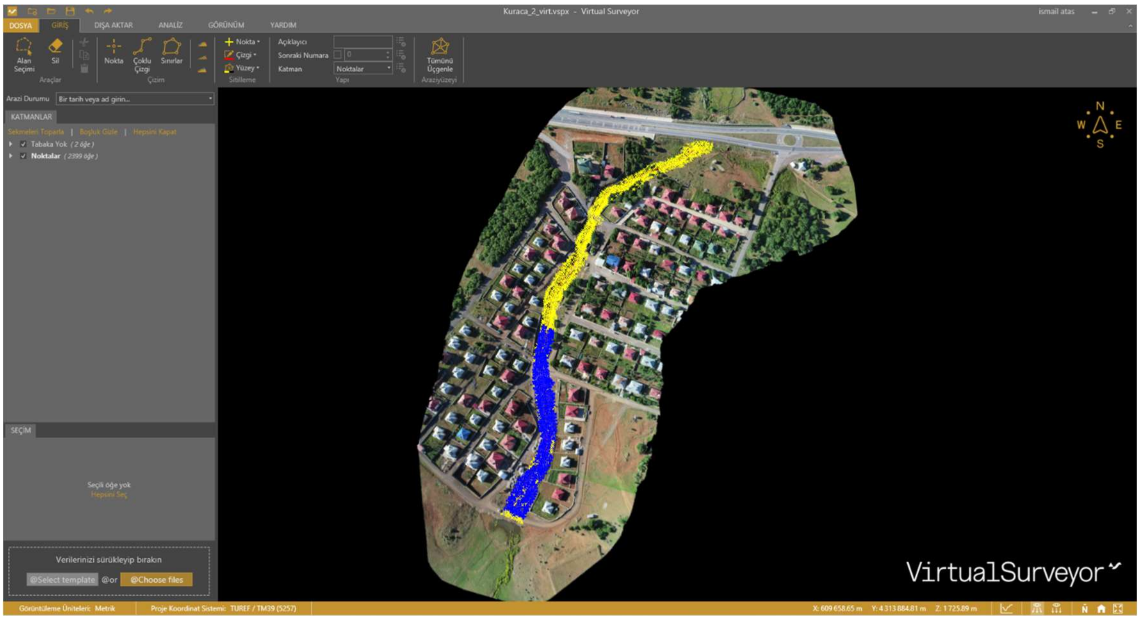

Figure 6. Screenshot of the Virtual Surveyor programme used during drawing.

Figure 7 displays the interface of the *NETCAD* program, another software utilized in the drawing process. *NETCAD* was essential for integrating the gathered data into a cohesive mapping system, ensuring the accuracy and precision of the final map.

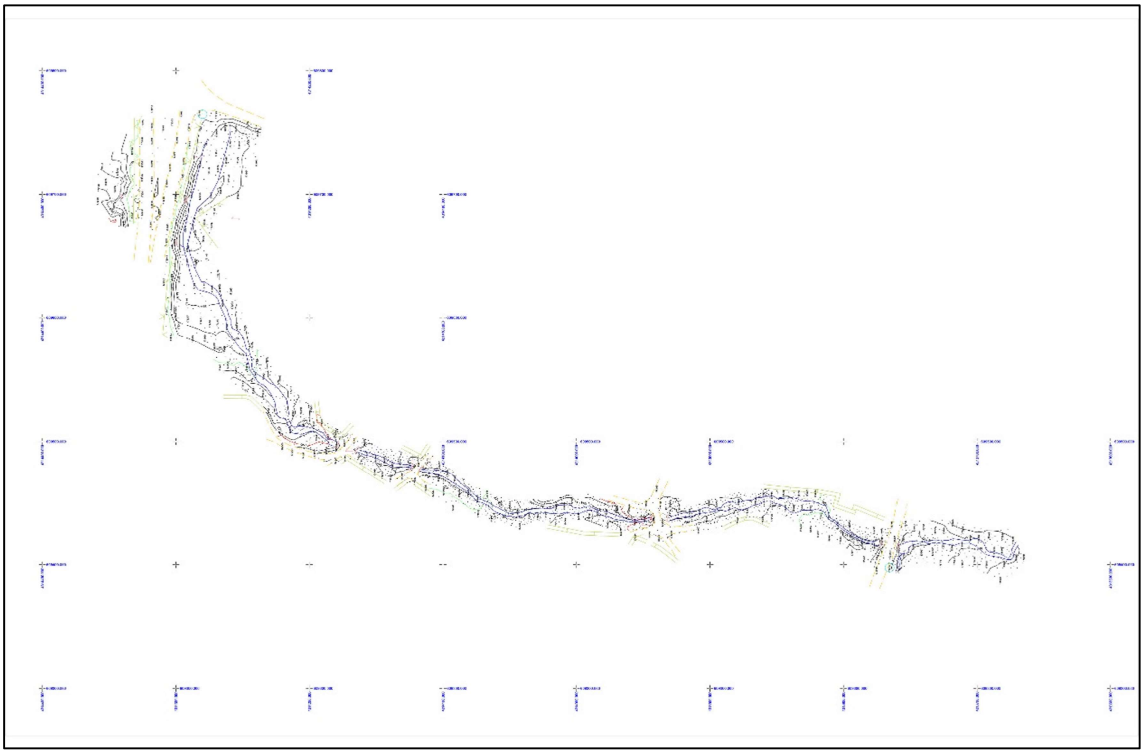

Figure 7. Screenshot of netcad programme used during drawing.

5. Discussion

This study presents the findings specific to the accuracy analysis of photogrammetric digital base map production, focusing on the results obtained from the Bingöl Central Kuruca Village example. The study thoroughly examines the impact of modern photogrammetric methods and technologies on accuracy, highlighting several critical findings:

1. Impact of the Distribution and Number of Ground Control Points (GCPs):
   One of the most significant findings in this study was the critical role of the distribution and number of Ground Control Points (GCPs) in determining the accuracy of photogrammetric maps. It was observed that a homogeneous distribution of GCPs greatly enhanced both horizontal and vertical accuracy parameters. Proper placement of GCPs ensures that the data coverage is more uniform, which leads to more reliable and precise mapping outputs.
2. Advantages of UAV Photogrammetry:
   The study demonstrated the substantial benefits of using Unmanned Aerial Vehicles (UAVs) for data collection in challenging terrain. UAVs have proven to be efficient in capturing high-precision data quickly and cost-effectively, even in areas that are difficult to access. This photogrammetric method has a significant advantage over traditional survey methods in terms of speed and cost-effectiveness, making it an ideal solution for large-scale mapping projects.
3. Impact of Focal Length on Accuracy:
   Another key finding was the noticeable effect of camera focal length variations on the accuracy of the photogrammetric results. It was established that optimal focal lengths enhanced the positioning accuracy of the collected data. Choosing the correct focal length is crucial as it directly influences the spatial resolution and, consequently, the overall quality of the final map products.
4. Role of Modern Software in Data Processing:
   The study highlighted the importance of using modern software tools, such as *PIX4D* and *Virtual Surveyor*, in processing photogrammetric data. These advanced programs played a vital role in improving the accuracy of the processed data. Their ability to

automate processes, streamline data analysis, and reduce error margins significantly contributed to the overall quality and precision of the final mapping products.

5. Horizontal and Vertical Discrepancies in Accuracy Analysis:
   The accuracy of the produced maps was assessed in terms of horizontal and vertical deviations. The findings showed that the deviation values met both national and international standards, demonstrating that the photogrammetric maps were in compliance with established accuracy thresholds. This supports the reliability of UAV-based photogrammetry as a credible mapping technique.
6. Comparison of UAV Photogrammetry with Traditional Methods:
   When comparing UAV photogrammetry to traditional topographic methods, the study found that the two approaches achieved similar levels of accuracy. However, UAV photogrammetry outperformed traditional methods in terms of data collection speed and overall cost-efficiency. The use of UAVs not only provides a faster alternative but also ensures better resource management during the mapping process.
7. Environmental Factors and Their Impact on Data Collection:
   Environmental factors such as terrain characteristics and vegetation coverage were found to have an impact on the data collection process. Despite these challenges, the study demonstrated that with careful flight planning and appropriate equipment selection, these environmental effects could be minimized. This underscores the importance of pre-flight analysis and strategic planning to ensure optimal conditions for data capture.
8. Accuracy of Digital Elevation Models (DEMs):
   The accuracy of the Digital Elevation Models (DEMs) produced by UAV photogrammetry was compared to those generated through traditional methods. The results indicated that UAV-derived DEMs provided higher accuracy levels, which are essential for applications such as topographic mapping and 3D modeling. This finding further reinforces the growing reliance on UAV technology for high-precision topographic data acquisition.

In conclusion, this study highlights the effectiveness of integrating modern photogrammetric methods and technologies in improving the accuracy of digital base map production. The analyses conducted on the Bingöl Central Kuruca Village example demonstrate that UAV photogrammetry, combined with advanced software tools and accurate ground control point placement, offers a reliable and cost-effective solution for modern mapping projects. The results of this study contribute to the growing body of knowledge on the applicability of UAV photogrammetry in various fields, reaffirming its role as a viable alternative to traditional surveying techniques in achieving high-quality geospatial data.

6. Conclusions

This study aimed to evaluate the accuracy and effectiveness of modern photogrammetric methods for the production of digital base maps, with a particular focus on UAV photogrammetry in the Bingöl Central Kuruca Village project. The research highlights the significant advantages of UAV-based photogrammetry in geospatial data acquisition, emphasizing its efficiency, cost-effectiveness, and accuracy comparable to traditional surveying methods. The optimal distribution of Ground Control Points (GCPs) and careful planning to mitigate environmental challenges were identified as critical factors in enhancing data quality. Furthermore, the optimization of focal length and the use of advanced software tools such as PIX4D and Virtual Surveyor played a key role in improving the accuracy of photogrammetric products. UAV-generated Digital Elevation Models (DEMs) demonstrated superior precision, particularly for applications requiring detailed topographic data. Overall, this study underscores UAV photogrammetry as a robust and versatile solution for modern mapping projects. Future studies are encouraged to explore the effects of environmental factors in greater detail and to conduct a more comprehensive comparison of the software utilized.

Conflicts of Interests
Authors declare that there is no conflict of interests

Financial Disclosure
Author declare no financial support.

Statement contribution of the authors
This study's experimentation, analysis and writing, etc. all steps were made by the authors.

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