

Evaluation of the Impact of Different Flight Planning Scenarios and Field Data on the Accuracy of Photogrammetric Products

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ABSTRACT:

The growing use of unmanned aerial vehicles (UAVs) and low-cost non-metric cameras in aerial photogrammetric surveys has highlighted the necessity and importance of optimal flight planning and control point design. This study was conducted to evaluate the effects of various flight design scenarios and field data configurations on the accuracy of photogrammetric products. Aerial image acquisition was carried out using two types of non-metric cameras over two study areas located in Yazd and Kerman, Iran. The influence of camera calibration, as well as the accuracy of tie point extraction, was assessed through aerial triangulation using both ground control points (GCPs) and check points (CPs). Subsequently, four flight design scenarios were analyzed, including:

1. Increasing the spacing between GCPs, 2. Reducing the longitudinal overlap, 3. Reducing the lateral overlap, and 4. Simultaneously reducing both longitudinal and lateral overlaps. For each scenario, error propagation and photogrammetric network accuracy were evaluated. The results indicate that the greatest variations in error occurred along the vertical (Z) direction across all scenarios, while horizontal components (X and Y) exhibited negligible changes. Overall, increasing the spacing between GCPs led to reduced accuracy at check points—particularly in the Z direction—despite lower residuals at the GCPs themselves. A reduction in longitudinal overlap resulted in higher errors in both study areas, while reduced lateral overlap mainly increased vertical errors. The simultaneous reduction of both longitudinal and lateral overlaps yielded the highest total error across the network.

1. INTRODUCTION

1.1 General Instructions

With the advancement of technology and the widespread adoption of unmanned aerial vehicles (UAVs), photogrammetry has evolved into a powerful tool across various disciplines such as surveying, civil engineering, agriculture, mining, natural resources management, and disaster management. Among these applications, UAV photogrammetry has gained a prominent position due to its advantages in terms of time efficiency, cost-effectiveness, data quality, and versatility, making it a valuable technique for spatial data acquisition at both terrestrial and aerial scales. (Senkal et al., 2021, Rock et al., 2012). The accuracy of photogrammetric products, such as three-dimensional models and orthophoto mosaics, is influenced by factors including flight design and the quality of field data. Considering its lower cost, higher spatial and temporal resolution, and greater flexibility in image acquisition compared to other aerial and satellite-based methods, UAV photogrammetry serves as an effective alternative to conventional mapping techniques. The number and spatial distribution of ground control points (GCPs) within the project area, as well as the optimal image acquisition strategy, play a critical role in the generation of accurate photogrammetric products and maps (Emami et al., 2022). Flight planning which includes determining the flight path, flight altitude, camera viewing angle, and the degree of image overlap is one of the key

factors contributing to the improvement of photogrammetric product accuracy. On the other hand, field data particularly ground control points (GCPs) play a crucial role in enhancing the accuracy of photogrammetric results. An appropriate number and optimal spatial distribution of these points can prevent systematic errors and ensure the precision of the final outputs. This aspect is of particular importance considering that most UAV photogrammetric cameras are non-metric. This study investigates the influence of various flight planning scenarios and field data configurations on the accuracy of photogrammetric products. Accordingly, the main objective of this research is to assess the effects of increasing the spacing between GCPs, reducing longitudinal image overlap, reducing lateral image overlap, and simultaneously reducing both longitudinal and lateral overlaps on the overall error within the photogrammetric network.

Flight planning and field data are therefore two key factors that fundamentally determine the accuracy of photogrammetric products. (Eisenbeiss, 2009). With advancements in image processing algorithms, investigating the interaction between flight design, field data, and modern software contributes to improving the accuracy and efficiency of photogrammetry. Network design in photogrammetry holds greater importance for achieving high accuracy in complex environments (Remondino et al., 2011). Factors influencing the final accuracy of products are determined during the flight design stage (Fraser, 1984). Furthermore, network design parameters, image

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observation quality, and aerial triangulation accuracy have direct and inverse effects, respectively, on the precision of 3D reconstruction (Latifzadeh et al., 2023). Various methods have been proposed for UAV flight network design. At ETH Zurich, a Digital Surface Model (DSM) was utilized for designing archaeological flights (Erfanzadeh et al., 2021). Additionally, the FMS algorithm has been suggested for maintaining constant flight altitude (Eisenbeiss et al., 2011). Examination of camera orientation has shown that the use of oblique images enhances point cloud density and vertical information accuracy (Gonzalez et al., 2017). Moreover, an imaging system with five oblique cameras improves urban modeling accuracy by approximately 30% (Chiabrando et al., 2017). Research has demonstrated that optimal distribution of ground control points increases photogrammetric accuracy. The best results are achieved with edge and stratified distributions, and combining these two reduces data errors (Yang et al., 2022). Furthermore, distributing points at the center and around the block provides better accuracy in urban and non-urban areas compared to peripheral models (Martínez-Carricondo et al., 2018). For greater precision, elevation control points should also be considered at the surface and center of the photogrammetric block (Dorzadeh et al., 2023). The use of a combination of oblique and vertical cameras also leads to improved modeling accuracy (Abbaspour et al., 2018). Environmental factors such as wind, light, and flight time affect image quality and the efficiency of photogrammetric operations. Longitudinal and lateral image overlaps have a significant impact on photogrammetric accuracy. Increasing overlap results in improved accuracy of 3D models (Amrullah et al., 2016). These studies indicate that appropriate adjustment of design parameters, ground control point distribution, and imaging method selection play a fundamental role in the quality of photogrammetric products and optimization of results.

2. BASICS

Proper design of the UAV photogrammetry network comprises two components: flight design and ground control point design. In flight design, camera selection is based on lens characteristics and focal length, flight altitude is chosen to ensure safety and accuracy, and the orientation of flight strips is adjusted according to the region's weather conditions and topography. Furthermore, the combined longitudinal and lateral image overlaps should not be less than 130%, and flight stations should be positioned at elevated and unobstructed locations. Ground control points are distributed to cover the area in both planimetric and altimetric dimensions. To enhance accuracy, these points are denser along the margins of the area and sparser at the center. Targets must also be large and distinct to facilitate easy identification in images and prevent displacement. Control points possess precise coordinates for image adjustment, whereas check points are solely utilized for assessing model accuracy. In the aerial triangulation process, the three-dimensional coordinates of image tie points are determined. This stage encompasses feature extraction and matching, image block formation, and the elimination of erroneous observations. Camera calibration is conducted to rectify geometric distortions and determine its interior orientation parameters. This process involves computing distortion coefficients and correcting optical parameters. Interior orientation establishes the coordinates of the principal point and pixel scales, while exterior orientation ascertains the camera's position and attitude in space via the projection center coordinates and rotation angles. Among photogrammetric errors, longitudinal, lateral, vertical, pixel, and reprojection errors can be noted, which influence the accuracy of three-dimensional models.

3. METHODOLOGY

According to figure 1, the process of implementation of the research is as follows:

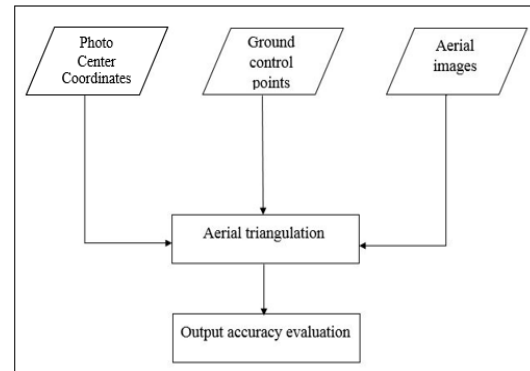


Figure 1. Flowchart of the Research Procedure

Initially, the images were aligned with a density of 20,000 for keypoints and tie points. Tie points appearing in two or more images are converted into keypoints to establish positional consistency. Subsequently, the coordinates of control points are refined.

Camera calibration is performed in two stages:

- 1- Recording all parameters and identifying dependent parameters.
- 2- Removing dependent parameters and recording results.

This process eliminates dependencies between parameters and creates an optimized mathematical model that minimizes the impact of lens distortion errors.

3.1 Airborne triangulation

To enhance the accuracy of the three-dimensional model, tie points that appear only in two images are removed. Two methods have been considered to investigate the impact of this removal on the model's accuracy:

- 1- Check points are placed alternately with a spacing of 1 kilometer, and two-image tie points are eliminated.
- 2- Check points are examined every other one with a spacing of 2 kilometers.

The errors of check points in these two scenarios and between the two study areas are compared. Based on the results of calibration and tie point removal, these steps will be assumed in the continuation of the research.

3.2 Proposed Method

Investigation of the Effect of Increasing the Distance of Control Points

In this scenario, four states are examined:

State 1: Triangulation using all control points.

States 2 to 4: The average distance of control points increases by 1, 2, and 3 kilometers respectively, with the remaining points considered as check points. The error values of control and check points in each state were compared.

The Yazd study area in the four states respectively: control points: 4, 6, 12, 30 and check points: 26, 24, 18, 0.

The Kerman study area in the four states respectively: control points: 4, 6, 12, 39 and check points: 35, 33, 27, 0. Investigation of the Effect of Reducing Longitudinal Image Overlap

First, the longitudinal image overlap is reduced, followed by triangulation in three states with control point distances of 1, 2, and 3 kilometers. The results are compared with scenario one. State 1 of scenario one is not executed in this scenario. The errors of control and check points are compared before and after reducing the longitudinal overlap, and additionally, the difference in check point errors between the Yazd study area and the Kerman study area is examined.

2.1.1 Study of the effect of reducing cross cover of images
in this scenario, the cross cover of images decreases and triangulation is performed in three cases, the distances between control points 1, 2 and 3 km. The results are compared with scenario 1. The error of control and check points, before and after the decrease of cross covering and also the difference of check points between the study area of Yazd and the study area is investigated.

2.1.2 Investigation of the Effect of Reducing Lateral Image Overlap

In this scenario, the lateral image overlap is reduced, followed by triangulation in three states with control point distances of 1, 2, and 3 kilometers. The results will be compared with scenario one. The errors of control and check points are examined before and after reducing the lateral overlap, and additionally, the difference in check point errors between the Yazd study area and the Kerman study area is examined.

2.1 Study area

This research was conducted in two distinct study areas. The Yazd study area covers 12.2 square kilometers, with the project comprising 1157 images and 30 control points. The number of initially extracted points was 2,451,878, which reduced to 1,083,571 points after removing two-image tie points. The images in this project were aligned at the highest precision level, with a density of 20,000 for tie points and 20,000 for keypoints.

The Kerman study area spans 9.1 square kilometers and includes 1047 images and 39 control points. The number of initially extracted points was 2,117,089, which decreased to 808,346 points following the removal of two-image tie points. The images in this project were aligned at the highest precision level, with a density of 20,000 for tie points and 20,000 for keypoints.

4. RESULTS AND DISCUSSION

Initially, the impact of the dependency among camera calibration parameters and the removal of two-image tie points is examined.

4.1 Investigation of the Effect of Dependency in Camera Calibration Parameters

In camera calibration, parameter dependency causes changes in other parameters, and dependent parameters must be removed, which was evaluated through the variance-covariance matrix. If the dependency exceeds 96%, the parameter with the lower coefficient is retained. Performing calibration with all parameters for the Yazd study area reduced the total residual lens error to 1.34 pixels. Dependencies exist between parameters K3 and K4, K2 and K3, and K1 and K2. The mean reprojection error was 1.34 pixels, and the total error on control and check points was 2.84 centimeters. Subsequently,

parameters K2, K3, and K4 were removed one by one, and the results were re-examined, with the residual lens error after parameter removal reaching 1.35 pixels. The mean reprojection error of tie points was 1.35 pixels, representing an increase of 0.01 pixel compared to calibration with all parameters. The total error on control and check points was 2.88 centimeters, which increased relative to the initial calibration. Ultimately, the dependency between parameters was eliminated, yielding an optimized model.

In calibration with all parameters for the Kerman study area, the total residual lens error was reduced to 0.981 pixels. The mean reprojection error was 0.981 pixels, and the total error on control and check points was 1.603 centimeters. Subsequently, parameters K2, K3, and K4 were removed one by one, and the results were re-examined, with the residual lens error after parameter removal reaching 1.01 pixels. The mean reprojection error of tie points was 1.01 pixels, showing an increase of 0.029 pixels compared to calibration with all parameters. The total error on control and check points was 1.634 centimeters, which increased relative to the initial calibration.

4.2 Investigation of the Effect of Tie Point Extraction Accuracy on the Overall Accuracy of the Photogrammetric Network

To investigate the effect of tie point quality on triangulation, points with higher and lower confidence levels were evaluated. Initially, all tie points for the Yazd study area were utilized in the triangulation process. Subsequently, tie points observed in fewer than three images were removed.

4.3 Investigation of the Effect of Removing Two-Image Tie Points

The weight settings for the Yazd study area were configured with camera measurement precision based on meters and degrees at 10000, control point precision at 0.005 meters, and scale precision at 0.001. The control point precision was 0.5 pixels, and the tie point weight was 1/3 pixel. Following the removal of two-image tie points, the x and y errors, along with the mean reprojection error, increased, whereas other parameters decreased. At a 1-kilometer distance, the removal of two-image tie points resulted in a reduction of errors, except for the mean reprojection error, which increased. The highest errors in control points were associated with z and total, while in check points, they pertained to x and total. At a 2-kilometer distance, the x and y errors in control points decreased, while those in check points increased; however, the z and total errors decreased. In comparing the two states (every other and every second), the x error decreased in the first state and increased in the second. Overall, the error in the every-second state was 2 centimeters greater. The y error in the every-second state was 16 centimeters greater, and the z error in the every-other state was 4 times greater than in the every-second state.

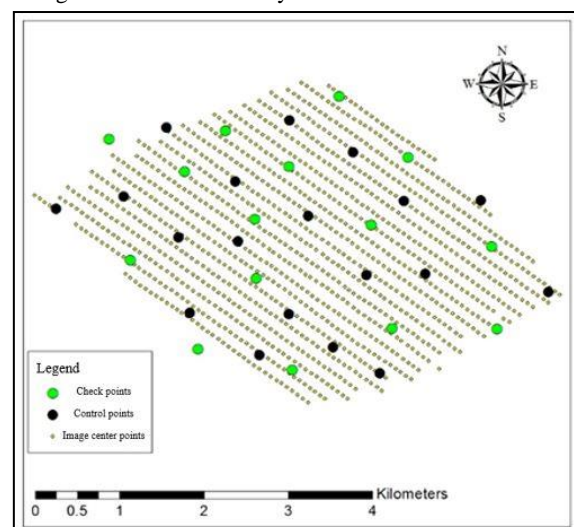


Figure 2. Distribution of Check Points with an Average Distance of 1 Kilometer for the Yazd Study Area in the Pre-Processing Stage.

Investigation of the Effect of Removing Two-Image Tie Points
The weight settings for the Kerman study area were configured with camera measurement precision based on meters and degrees at 10000, control point precision at 0.005 meters, and scale precision at 0.001. The control point precision was 0.5 pixels, and the tie point weight was 1 pixel.

At a 1-kilometer distance, unlike Yazd, the control point errors decreased, while the check point errors increased. With the increase in check point distance to 2 kilometers, the trend of changes was similar to the previous stage. In comparing the two areas, the overall error in the Yazd study area was greater than in the Kerman study area. In the Yazd study area, the highest and lowest errors were associated with total and x, respectively, while in the Kerman study area, they were associated with total and y.

The x, y, z, and total errors decreased in Yazd and increased in Kerman. The pixel error decreased in Yazd but remained constant in Kerman. The mean reprojection error in Yazd increased after removing two-image tie points, whereas it decreased in Kerman. In the every-second distribution, the error behavior was the opposite of the every-other distribution; in Yazd, x and y errors increased, and in Kerman, all four errors increased. Overall, removing two-image tie points did not have a substantial impact on the errors, except for z and total errors, which changed by an average of up to 10 centimeters.

4.4 Investigation of the Effect of Increasing the Distance of Control Points

In this scenario, for both study areas, four states will be evaluated. In state one, all points are considered as control points. In state two, control points are placed with an average distance of one kilometer from each other, and the remaining points are regarded as check points. In states three and four, the average distance of control points will be two and three kilometers from each other, respectively, with the remaining points considered as check points. The results of examining the control point distances and photogrammetric accuracy in the Yazd study area indicate that doubling the control point distance caused a 2.5-fold increase in z and total errors; however, tripling this distance resulted in a 1.5-fold increase in these errors.

In the Kerman study area, doubling the control point distance led to a 2-fold increase in z and total errors; whereas tripling this distance resulted in a 9-fold increase in these errors. Increasing the control point distance has a noticeable impact on the z error; however, it does not induce substantial changes in x and y errors. If elevation accuracy (z) in photogrammetry is not critical, the control point distance can be increased, thereby reducing the operational cost and time. In this scenario, the variation in z error stemmed from the increase in control point distance, while the network and longitudinal and lateral overlaps remained constant.

Investigation of the Effect of Reducing Longitudinal Image Overlap

Increasing image overlap leads to a heightened probability of identifying corresponding points and enhanced computational accuracy. On the other hand, the objective is to reduce the cost and time associated with imaging for the production of photogrammetric products. This is achieved by removing images every other one, followed by processing in three states where the control point distances are sequentially increased to one, two, and three kilometers, respectively. It is noteworthy that state one of scenario one, in which all points were designated as control points, is not executed subsequently.

The Yazd study area was imaged with 84% longitudinal overlap and 55% lateral overlap. In the first state, the longitudinal overlap is reduced to 67%, the lateral overlap remains constant, and the average control point distance is one kilometer. In the second state, the longitudinal overlap of images is reduced to 67%, and control points are configured with a two-kilometer distance. In the third state, similarly, the longitudinal overlap of images is reduced to 67%, and control points are configured with a three-kilometer distance. The Kerman study area was imaged with 82% longitudinal overlap and 60% lateral overlap. In the first state, the longitudinal overlap is reduced to 63%, the lateral overlap remains constant, and the average control point distance is one kilometer. In the second state, the longitudinal overlap of images is reduced to 63%, and control points are configured with a two-kilometer distance. In the third state, similarly, the longitudinal overlap of images is reduced to 63%, and control points are configured with a three-kilometer distance.

4.5 Investigation of the Effect of Reducing Lateral Image Overlap

In this scenario, for both study areas, the lateral overlap is initially reduced. This is achieved by removing flight lines every other one, followed by processing in three states where the control point distances are sequentially increased to one, two, and three kilometers, respectively. It is noteworthy that state one of scenario one, in which all points were designated as control points, is not executed subsequently. In the first state for the Yazd study area, the lateral overlap is reduced to 10%, the longitudinal overlap remains constant, and the average control point distance is one kilometer. In the second state, the lateral overlap is reduced to 10%, and control points are configured with a two-kilometer distance. In the third state, similarly, the lateral overlap is reduced to 10%, and control points are configured with a three-kilometer distance.

In the first state for the Kerman study area, the lateral overlap is reduced to 19%, the longitudinal overlap remains constant, and the average control point distance is one kilometer. In the second state, the lateral overlap is reduced to 19%, and control points are configured with a two-kilometer distance. In the third state, similarly, the lateral overlap is reduced to 19%, and control points are configured with a three-kilometer distance.

4.6 Investigation of the Effect of Simultaneous Reduction in Longitudinal and Lateral Image Overlaps

In this section, for both study areas, the longitudinal and lateral overlaps were simultaneously reduced. This was achieved by alternately removing flight strips and images. The processing was then carried out under three conditions, in which the spacing between ground control points (GCPs) was increased to 1 km, 2 km, and 3 km, respectively. It should be noted that the

initial scenario Scenario 1, in which all points were used as control points was excluded from this stage of analysis.

4.7 Results Evaluation

The results indicate that the removal of dependent parameters in both study areas led to an increase in the total lens error, residual error, and mean reprojection error. If vertical accuracy (Z) is not a critical factor in photogrammetric projects, the spacing between ground control points (GCPs) can be increased, thereby reducing both operational time and cost.

In Scenario 2, where the longitudinal overlap of images was reduced in combination with increasing GCP spacing (tested in three configurations) for both study areas, the control point errors before and after overlap reduction showed a decreasing trend, inversely related to GCP spacing. Reducing longitudinal overlap led to a decrease in the control point errors. However, the errors of the check points exhibited an increasing trend, directly related to the GCP spacing. Thus, reducing longitudinal overlap caused an increase in check point errors.

In Scenario 3, where the lateral overlap of images was reduced while increasing the GCP spacing (again in three configurations) for both study areas, the control point errors before and after overlap reduction followed a decreasing trend, inversely related to GCP spacing. Reducing lateral overlap resulted in a decrease in control point errors. Conversely, the check point errors showed an increasing trend, directly proportional to the GCP spacing. Hence, reducing lateral overlap led to an increase in check point errors. Simultaneous reduction of longitudinal and lateral overlaps decreased the control point errors, but had different effects on check point errors in the two study areas. In the Yazd area, this reduction in overlap slightly decreased the check point errors, whereas in the Kerman area, it led to noticeable increases in total, X, Y, and Z errors.

In the Yazd study area, when the spacing between GCPs was doubled, the Z-error increased by approximately 2.8 to 3.8 times, and when the spacing was tripled, the Z-error increased by 4.0 to 4.5 times. Similarly, both the Z and total errors increased by about 3.6 to 3.9 times. In the Kerman study area, doubling the GCP spacing increased the Z-error by 1.8 to 2.3 times, and tripling the spacing caused an increase of 8.9 to 26 times. The Z and total errors increased by approximately 1.7 to 26 times. Overall, the reduction of longitudinal and lateral overlaps did not produce uniform effects across the two study areas. In Yazd, these changes reduced errors, while in Kerman, they caused a significant increase—especially in the Z-direction. Additionally, the type of camera used played an important role in the magnitude of the observed errors.

5. CONCLUSION

The proper selection of camera type and flight mission parameters is essential for achieving high-accuracy photogrammetric operations. The results of this study demonstrate that optimizing camera calibration, eliminating parameter dependencies, and accurately selecting tie points play a critical role in enhancing the precision of photogrammetric products.

A comparison between the two study areas, Yazd and Kerman, revealed that the removal of dependent parameters and low-confidence tie points had varying effects on 3D model reconstruction errors and reprojection errors. These variations depend on the geometric characteristics of the terrain and the

image coverage pattern, indicating that error behavior changes according to the structural geometry and photogrammetric configuration of the area.

Furthermore, increasing the spacing between ground control points (GCPs) had the greatest impact on elevation (Z) errors. When high vertical accuracy is not required, GCP spacing can be increased to improve efficiency and reduce operational costs. Reducing both longitudinal and lateral overlaps—individually or simultaneously—resulted in a decrease in control point errors but an increase in check point errors, particularly under conditions of increased GCP spacing.

The findings from the Yazd and Kerman study areas confirmed that reducing image coverage does not have a uniform effect; it varies based on regional characteristics and the spatial distribution of control points. Overall, integrating proper management of parameter dependencies, optimizing flight design, and carefully monitoring tie point quality can substantially enhance the efficiency and accuracy of aerial photogrammetric modeling.

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