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Analysis and Design of Protocol for the Reconstruction of Computer Field Model Using Dron and Photogrammetry

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Abstract: One of the main challenges in aerial photogrammetry is the lack of standardization in the process of data integration, which is the first step in 3D reconstruction. This study analyses the influence of the distance from the camera to the subject of the recording, the influence of different overlap percentages in photography as well as the difference between the three methods of re-cording in programming flight plans. DJI Phantom 3 unmanned aerial vehicle and PIX4Dmapper software for 3D reconstruction were used in this research. The old town of Medvedgrad near Zagreb, Croatia was the subject of recording. The purpose of this study is to design a standardized image recording protocol that would contribute to a faster and more optimal workflow while maintaining a quantitatively measured quality according to the total number of 2D key points per image and the total number of 3D key points in a point cloud. Based on research and the obtained results, the possibility of data recording at a distance of up to 30 m without a significant loss (3.6%) of the number of 2D key points per photograph was proven. A larger horizontal distance allows recording from one viewing altitude if the height of the subject does not exceed 30 m. This study determines that 85% image overlap results in an almost identical number of 3D key points (0.7% difference) as well as 90% image overlap. The authors proposed a new flight plan, which would implement optimized parameters obtained in this research.

Keywords: Data Integration, Point Cloud, PIX4Dmapper, UAV Photogrammetry

Introduction

Unmanned Aerial Vehicles (UAVs) equipped with high-resolution cameras have become increasingly affordable, leading to the rapid growth of specialized aerial photogrammetry software. Aerial photogrammetry refers to the use of UAVs, such as drones, airplanes, helicopters, etc., to collect data through photography. However, this rapid development has resulted in a lack of standardization, particularly in the data collection process and the choice of flight plan. Current recording methods are often generalized and do not account for specific situations, creating ambiguity in determining the appropriate horizontal distance between the camera and the subject (Raczynski, 2017).

The selection of percentages in image overlap, which is directly correlated with the total number of images, is also not standardized. Available research offers a wide range of recommended overlaps from 70-80% (Barba *et al*., 2019) to 90% (Koch, 2020). The difference between these percentages in certain projects can represent up to several thousand images. In the aerial photogrammetry workflow, taking images requires a large number of working hours spent on the field. It should be taken into account here that the battery capacities (in our case a battery-powered drone) of unmanned aerial vehicles are not large, so the measurement cannot be performed during one flight or in a single day. Meteorological conditions should be taken into consideration, the position of the sun, the speed of wind, humidity, and air temperature as well as the control of airspace and the whole area (Yepes Moya, 2020). Therefore, reducing the number of required images will speed up the process of 3D reconstruction. New UAVs utilize better Inertial Measurement Unit (IMU) technology and satellite connections for precise positioning during aerial photography, eliminating the need for expensive ground control points in conventional photogrammetry (Tucci *et al*., 2018). By using IMU and GPS, the reconstruction software directly retrieves the global coordinates from the images themselves and can in such a way reduce the total project time by 15% according to Barba *et al*. (2019). The study is based on the number of detected 2D and 3D image key points using Pix4Dmapper software, known for its reliability in photogrammetry (Tucci *et al*., 2018). Previous research has demonstrated the correlation between a higher number of images and the quality of the point cloud and computer model (Koch, 2020; Yepes Moya, 2020). Furthermore, increasing photo resolution improves the accuracy of the point cloud, according to Tucci *et al*. (2018). These facts allow for comparing measurement methods based on the same object's surface area. If the number of detected key points per image remains constant, there will be no impact on the point cloud or model. Reducing the image overlap percentage can decrease the total number of images required for a project, which is particularly important for large-scale measurements (Saadatseresht *et al*., 2015). During the pre-research activities, an issue of aerial photogrammetry was found in scientific papers in the field of photogrammetry, three-dimensional reconstruction, and unmanned aerial vehicles. As this is a relatively new technology that has so far been professionally applied only in specialized industries, issues can be seen in all the phases and activities of aerial photogrammetry. This presents a great challenge since every activity from project planning, flight planning, recording of a subject, and software work are directly correlated with the final result of the computer model.

Today there are several dozen unmanned aerial vehicles on the market, which, according to the manufacturers' specifications, apparently have the same performances. However, the large difference in price range proves this not to be true. The difference can usually be seen in the quality of the camera sensor, GNSS receiver, and the flight length, which determines the battery capacity. On the contrary, the battery capacity, among other factors, affects the length of the flight, which is important for such experimental purposes. Currently, the only standardized regulation relates only to the operating mass of the aircraft. When referring to the quality of GNSS receivers, it should be noted that Ground Control Points (GCPs) are used for professional purposes. As it is very important to record the position of the cameras accurately, GCP markers are manually implemented for professional purposes, which, aided by mobile GPS systems, increase the accuracy below a centimeter. However, the use of ground control points is very expensive and requires additional fieldwork that can be quite dangerous in certain cases (Koch, 2020). In this study, Koch (2020) also refers to research from 2014 that claims the use of terrestrial checkpoints takes up at least 15% of the time in the entire data collection process. Therefore, the research project does not use GCP systems but relies on an internal GNSS aircraft receiver. There are several elements that can be optimized in the process of data collection, i.e., in aerial photography. One of those elements is the number of vertical horizons. In other words, at what altitude should the aircraft measure the subject or field in order to capture all the necessary data? With higher subjects, this could require several recording altitudes. By increasing the recording altitude, the accuracy of the final model is reduced (Yanagi and Chikatsu, 2016). Apart from Yanag and Chikatra similar issues were investigated by Saadatseresht *et al*. (2015). The paper discusses the capturing of extensive areas through high-volume photography and highlights the significant impact of reducing the percentage of overlap on the overall number of images required. There are a number of different opinions as to what the optimal percentage of image overlap is. While Yanag and Chikatsu recommend an 80-90% overlap, Koch (2020) recommends an overlap of at least 70-80%.

Concerning the software part of aerial photogrammetry, several elements have been discovered that require further work. Remondino and Stylianidis (2016) write about the lack of automation in working with software. They also mention actions that are not part of the reconstruction process such as key point search, point cloud, and polygon creation, required manual and additional time-consuming work. Those who do not work with reconstruction software are not familiar with the work done in that segment. Certain programs require selecting parts of images that were not supposed to be reconstructed. The use of such programs and actions can drastically increase the duration of a project. Prior to entering the images into the software, it is necessary to check their quality and, if necessary, adjust certain parameters or remove the shadow. All these tasks are done manually. Therefore, it is necessary to automate certain processes. Gruen *et al*. (2012) discuss the lack of automation and standardization in their research. The lack of standardization in aerial photogrammetry processes results in poor or non-existent quality control. In all industries, quality control is the last stage of the process: Control of products or services before they are launched. In order to reduce the volume of data processing, which is mentioned above, significant human and time resources are needed. It is also necessary to perform a quality data collection process through recording that requires the correct settings of the aircraft and the camera.

All images should be taken under the same conditions and settings. Additionally, it is essential to review all the captured images thoroughly on-site, preferably during instances when the aircraft is grounded for tasks such as battery replacement or completion of work. This visual inspection enables the identification of specific image selections that do not meet the desired quality criteria and prevents additional work in the software itself (Remondino and Stylianidis, 2016). However, not all authors have a positive opinion about the complete automation of the photogrammetry work process. Tucci *et al*. (2018) say in their paper that leaving full control of the computer has negative sides in terms of additional education and expertise in these fields. They imply that the need for professional people is lost and that the people who will manage these systems will not know the technical and theoretical basics of the services they offer.

A critical academic study was conducted by Tysiac *et al.* (2023), utilizing a combination of Unmanned Aerial Vehicle (UAV) photogrammetry and Terrestrial Laser Scanning (TLS), to develop a three-dimensional model of the church more accurately. Alongside the compilation of extensive historical inventory documentation, this study generated a comprehensive Historical Building Information Model (HBIM) using the Autodesk-Revit® modeling software. Leveraging the generated model, a methodology was proposed to analyze the degradation of the church's components, incorporating the reflection properties of the laser scanner beam and Red Green Blue (RGB) images. The primary hypothesis of this research centers around the analysis of sunlight exposure outside the church. Apart from its significance in assessing the risks of church degradation, the study also presents a high-quality visualization method that combines the TLS and UAV photogrammetric techniques.

The study from Kanun *et al.* (2022) focuses on digitally documenting and creating a 3D model of an ancient village house in Kanytellis, representing one of these ancient cities. The study also includes calculations of the building's area and volume, derived from measurements taken on the 3D model. Two different software, Agisoft meta shape, and context capture were used for analysis and the results are presented comparatively in the study's results section. A difference of 1.32 cm was observed between the models during the analysis. It is anticipated that the reconstructed model will contribute to the preservation of Turkey's historical and cultural heritage, ensuring its transfer to future generations and fostering the development of tourism activities.

In addition, Cavalagli *et al*. (2020) in their research paper present a methodology for performing a photogrammetric survey using UAVs on a masonry arch bridge of historical significance located along the ancient Via Amerina in Todi, Perugia, Italy. The objective was to conduct effective visual inspections and generate a detailed 3D model of the bridge. The photogrammetric survey successfully captured the precise geometry of the structure, revealing the presence of voids and significant cracks along the vault and spandrel walls, indicating severe damage. To validate the photogrammetric results, a total station and a laser scanner were employed, allowing for a comparative analysis that highlights the advantages, limitations, and weaknesses associated with each method.

By reviewing research papers and literature, the areas of aerial photogrammetry that require further work can be listed. Not only through the development of new technology in terms of better and more intelligent computer algorithms but also through the standardization of devices, terminology, technology, and workflow protocols. Here are potential areas for enhancing efficiency and optimization:

1. Optimal hardware selection, such as Unmanned Aerial Vehicles (UAVs) that align with the intended activity, along with suitable software for 3D reconstruction and appropriate recording technologies
2. Standardizing the workflow across all aerial photogrammetry steps
3. Accelerating data collection through the incorporation of automation processes while maintaining the quality of the final model
4. Substituting the use of Ground Control Points (GCPs) with high-quality internal GNSS receivers
5. Incorporating greater interactivity and manipulation during the 3D reconstruction steps, including point cloud generation, polygonal modeling, and texture mapping

3D Reconstruction Software-PIX4Dmapper

Aerial photogrammetry involves two elements: Data collection through Unmanned Aerial Vehicle (UAV) field recording, followed by software-based photogrammetry. Various 3D reconstruction software options exist, with studies like Shahbazi *et al*. (2015) "Development and evaluation of a UAV-photogrammetry system for precise 3D environmental modeling" influencing the selection of PIX4Dmapper for this research project. PIX4Dmapper, developed by a Swiss company, specializes in field and building reconstruction, offering versions tailored to different industries (e.g., PIX4D BIM for construction, PIX4D Ag for agriculture, PIX4D Model for real estate). The "PIX4D Capture" application enables automated control and field recording using UAVs, allowing users to choose flight patterns or create custom plans, determine recording frequency, altitude, and overlap percentage, and switch between manual and automatic control. The software provides a wide range of tools, including analytical tools, unique reference point detection, global point cloud generation, and editing capabilities. The reconstruction process starts with the initial detection of key points and extraction of Earth coordinates from image metadata. Accurate camera positions enhance key point correlations and improve the computer model. Key points are crucial in image processing and PIX4Dmapper uses the Scale Invariant Feature Transform (SIFT) algorithm to detect and describe local 2D key points. SIFT ensures size and brightness variations have minimal impact on key point detection, accommodating images captured from different distances and lighting conditions. The SIFT algorithm comprises four components: Dimension application and extreme detection, key point localization, orientation alignment, and key point vector description.

Initial Detection of Key Points

Once the images are entered into the software, the first reconstruction step begins the initial detection of key points for each individual image. Parallel with the detection, the system extracts the earth coordinates stored while taking images from the image metadata. The camera location, orientation, and camera angle were accurately detected via satellite for each image taken. This data will serve the system so it can correctly upload the images in its local coordinate system.

Precise camera positions increase the number of correlations between key points and in this way provide a more accurate computer model.

Features or key points in an image represent an important segment in image processing. Each image has thousands of unique key points that appear only once per image. In further steps, the software performs the extraction of key points (key point vector), i.e., their description that will be searched in neighboring images. If it finds them, there is a correlation or overlap.

The program has two tasks. Find the most prominent key points so they can be more easily detected in later procedures and at the same time have measured in detection so that the whole program is not completely slowed down with tens of thousands of key points per image. PIX4Dmapper solves this balance by using the SIFT algorithm.

SIFT Algorithm, Dimension Application, and Detection of the Extremes

Scale Invariant Feature Transform (SIFT) algorithm belongs to the computer vision field. It is used to detect and describe local 2D photography key points. One of the key features is the fact that changing the size and brightness of the image has no effect on the detection of correlation key points. This is important if the images have not been taken from the same distance, which results in different sizes of key points, and in turn certain programs may not recognize them. Another element that can disrupt the discovery of identical key points is photography lighting. Images taken at different time intervals or conditions, such as shadows, early evening, and early morning, can cause identical key points to differ drastically across images.

The SIFT algorithm is composed of four elements one building onto another:

- Dimension application and detection of extremes
- Localization of key points
- Orientational alignment
- Key points record (vector description)

In this step, the image is divided into octaves, where each new octave is twice as small as the previous one. The number of octaves depends on the original image dimensions. Each octave is blurred separately using the principle of Gaussian curves, i.e., the "Gaussian blur" filter. After blurring the image, a set of new images is created, in which the Gaussian blurred versions of the original image are gradually removed and a new image is obtained, the differences of the Gaussian filters. In other words, a DOG step is taken as shown in Grenzdörffer *et al.* (2008) In this way, the algorithm detects which key points have the greatest ability of recognition, i.e., the greatest difference from neighboring local key points. The next step is to find the key points (2D features) on the image. The search is performed on an image with the difference in Gaussian filters. Each pixel in an image is compared to the neighboring 8 pixels as well as to two images of different dimensions (smaller and larger). This amounts to a total of 26 pixels (8+2×9), Eisenbeiß (2009). In this way, key points in different dimensions are detected. This makes the rule of comparison in images taken from different distances or image sizes possible.

Localization of Key Points and Orientational Alignment

In the above-mentioned step, the algorithm can find tens of thousands of key points. Since photogrammetry deals with thousands of images, this can drastically slow down the process of reconstructing 3D models. This step eliminates key points that are on pixel edges or do not have a high contrast. Such key points are not recognizable well enough and cannot represent the image's key points. Weak contrast is eliminated by using a Hessian matrix. Edge pixels are detected using the Harris corner detector which is deleted from the image key point list after detection.

Once the algorithm has precisely determined the key points of the images and their ability to be detected regardless of their dimensions, it is necessary to enable detection by changing its orientation. Photogrammetry, especially the aerial one, is taken not only from different horizontal positions but also from different heights and viewing angles. In these cases, the orientation of 2D key points is not the same. In order for this effect not to prevent correct detection and image aligning, the algorithm uses a local area histogram. Gray color gradation is measured around the detected key point. Vectors measure the size and direction of gradation, Martínez-Carricondo *et al*. (2018). In this way, key point features are recorded and, regardless of orientation, the algorithm will recognize identical vector records and align images correctly.

The algorithm has so far determined the image key point accurately and it enabled accurate detection regardless of size and orientation. The following step is the key point record format itself. The program forms a 16 by 16 window around the center of the 2D key point. This is then divided into 16 equal squares, resulting in a 4 by 4 window. For each of these 16 squares, an eight-part vector relating to the gray gradation is created in the previous step, Ferrer-González *et al*. (2020). The final vector key point record is a vector with 128 dimensions (4×4×8). This ensures fast and accurate detection of identical key points in other images.

Point Cloud

The second step in the reconstruction of the three-dimensional computer model starts with a search for correlated 2D key points, i.e., overlapping of 2D image key points. Although the algorithm searches all the entered images, it puts a special emphasis on neighboring images detected based on camera coordinates, angle, and lens orientation during recording. When an overlap is detected, the system calculates the exact location of the overlap using the triangulation method. As the program has the exact location of the camera position in its local coordinate system, drawing an imaginary line from the camera lens (known angle and camera orientation) results in a 3D key point located within the coordinate system. A set of all 3D key points is called a point cloud and can contain hundreds of thousands or millions of key points.

Creating Planes, Adding Textures and Exporting Model

Before the creation of the planes begins, it is necessary to clear the noise from the point cloud. These are incorrectly located points which can be determined by visual inspection. Pix4D has several tools that can be used to delete one or more misplaced 3D key points with a simple click of a mouse.

Apart from interference, edge sharpness or surface curvature can be adjusted, as well as various manipulations of the existing 3D key points, as well as the addition of new ones.

After the point cloud processing was completed, planes were added. Planes connect adjacent points (3D key points) and the accuracy of the reconstruction also depends on the number of 3D key points in a certain space. The final step is adding textures stored in the point cloud that contain RGB data for each image pixel.

Once the reconstruction of the computer model is completed, several possible steps can be taken. One of those possible steps is model manipulation or additional object optimization. Model adjustment tools allow movement of the endpoints on the plane, shaping the edges, and increasing or decreasing the curvature of the corner parts. It also offers the creation of new planes which could fill possible model defects. It offers a number of export models, including the. OBJ file format, which is compatible with many popular 3D modeling software and “gaming engine” software.

Materials and Methods

Research topic: This study analyzes the issues and disadvantages of aerial photogrammetry indicated in the researched professional literature. Based on the research, field measurements will be carried out by unmanned aerial vehicles to analyze different technical methods for data collection.

Maximum distance from the camera to the captured object without losing a number of image key points.

Minimum percentage of image overlap without significant (<1%) loss of the total number of key points in the point cloud.

Analysis of three flight plan types and measurement of the total number of key points in the point cloud and total flight time.

Research objective: The objective of this research is to determine the optimal and more efficient working mode in the process of data collection without losing the quality that can be quantified by the total number of key points (features) per image and the buried number of key points in the point cloud. Data collection processes include all the phases of field activities (field measurement using an unmanned aerial vehicle with correlation activities) as well as the preparation of these activities.

The contribution of this study is a standardized work protocol based on the optimization of the data collection process in aerial photogrammetry.

Measurement instruments and research process: The research project involved fieldwork using a DJI Phantom 3 Standard Unmanned Aerial Vehicle (UAV) to collect data and capture images of Medvedgrad. This UAV belongs to the light-medium weight category, weighing just over 1.2 kg, and has a quadcopter design with specific speed and ascent/descent rates. It features a 12-megapixel CMOS sensor with a 94-degree angle of view and f/2.8 lens, mounted on a stabilizing gimbal. The camera cannot be replaced, limiting sensor upgrades. The UAV is controlled by a remote with a frequency range and range limitations. It uses a DJI "intelligent flight" battery providing approximately 22 min of flight time. The CMOS sensor's rolling shutter capturing method can affect image sharpness and data integration in aerial photogrammetry. The UAV incorporates an internal GNSS receiver connecting to GPS and GLONASS navigation satellites, ensuring accurate location data recorded in image metadata. Control and planning were facilitated using the DJI GO application and PIX4Dcapture mobile app. Image processing involved checking each image in Adobe Photoshop before using PIX4Dmapper software for reconstruction into a 3D computer model. PIX4Dmapper supports JPEG and TIFF image formats, automatically extracting camera location coordinates from metadata. The software offers various analytical and data manipulation tools for measurement and analysis. The research focused on detecting unique reference points using PIX4Dmapper's analytical tool, considering the correlation between image quantity, resolution, point cloud accuracy, and the final model. Measurements and analyses were performed for each research problem independently.

The influence of (horizontal) distance of the camera position on the number of detected key points (features) in the image, calculated by PIX4Dmapper software, was chosen to be the first research problem. The research was carried out at five different locations (Fig. 1a). Horizontal distances amounted to 10, 20, 30 and 40 m. Vertical height in relation to the ground is 15 m, twice as low as the highest peak on Medvedgrad.

A graphical representation of the camera position in relation to the subject is shown in Fig. 1b.

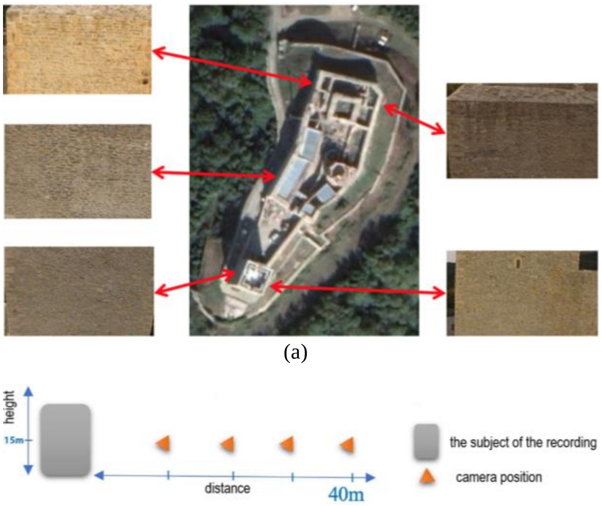
An image taken from a distance of 10 m is considered to be the base image. Since recording from a greater distance also covers a larger frame, Adobe Photoshop did additional image processing, such as cropping in order to obtain a frame from the base image. This additional process allows measurement of the same area and gives more representative results. Detection of key points (2D features) per image was performed on all 20 images using PIX4Dmapper software. Additional analysis shows the relations between distance and image key points. The results obtained represent the maximum distance from which shots can be made without losing the quality in detection. The obtained horizontal distance parameters were used to plan the research for the two remaining research points.

Mobile application PIX4Dcapture was used for the second research problem, i.e., for accurate recording according to the desired parameters. All flight parameters were set in the program for each recording activity. This includes the percentage of image overlap. Four image overlap settings were captured separately: 90, 85, 80 and 75%. The grid recording method was chosen since this recording method requires the highest number of images that result in the most accurate results. The unmanned aerial vehicle was taking images from a 50 m altitude. PIX4Dmapper software reconstructs a global point cloud for each of the four image overlap settings. The total number of 3D key points on the global point cloud is analyzed in relation to the percentage of image overlaps.

Three flight plans were created to capture Medvedgrad for the purpose of the third research problem, using the PIX4Dcapture application. The first two are predefined in the software itself: A double grid and circular motion around the center point. The authors created a hybrid from the above-mentioned plans based on the individual geometric features of the building itself. All methods have identical image overlap settings. PIX4Dmapper software creates a global point cloud for all three flight plans separately, each measuring the total number of 3D key points.

Figure 2 shows the entire research project workflow. It starts with defined project goals (CP) and created flight plans for the unmanned aerial vehicle (PL). The first data recording (SP), which is determined by the duration of the internal battery, is followed by photography quality control (KK) on the field. If the quality of the images is acceptable, the recording continues.

If this is not the case, a new plan is modified or an existing plan is being adjusted so that images that have not met quality control criteria could be retaken. The final, software part of the process (SO and 3D) starts at the end of the recording. This process is repeated for all three points of research.


(a)

(b)

Fig. 1: Research locations

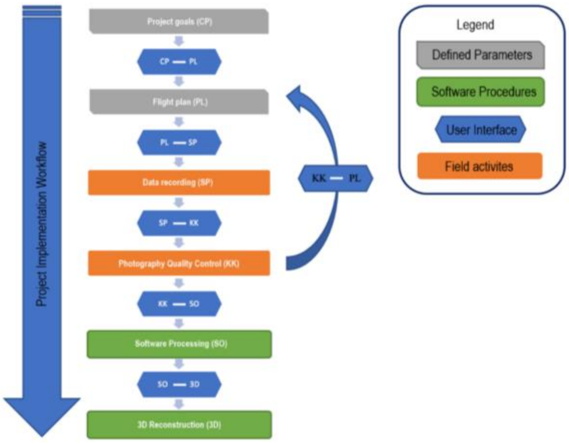
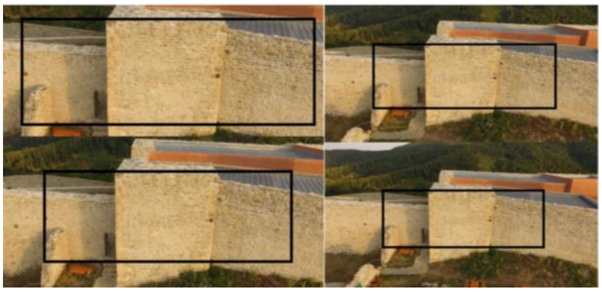


Fig. 2: Research project workflow

(a)



(b)

Fig. 3: (a) The author's flight plan; (b) Adjusting the research frame

Sample Recordings

Flying activities begin at the approved time. The first recording for the first (I.) research point took place on 20 June from 6:45-8:15 A.M. Prior to taking specific 20 images at five different locations, a reference sample is taken. The chosen method for recording is a circular motion around the center of Medvedgrad. 90 percent image overlap was selected, with a horizontal flight speed of 3 m/s, at a 50 m altitude.

Afterward, the recording started at five different locations on Medvedgrad, as shown in Fig. 4. The horizontal distance from the unmanned aerial vehicle to the subject was 10, 20, 30 and 40 m, at 15 m in height. At each location, two images were taken for each distance in case some of the original images did not meet the quality. One image per distance will be used in the analysis, which is a total of 20 images for research point one (I-1).

The time of scheduled and completed recording for research point I-2. is June 26, from 7:00-9:00 A.M., and June 27, from 7:30-9:00 A.M. The flight plan was created using the PIX4Dcapture application.

A predefined "double grid" flight plan at 50 m altitude was used, with a slow + horizontal speed of the unmanned aerial vehicle and an 80-degree imaging angle. The first recording was set to 90% image overlap. The entire flight operation lasted about 65 min, including two landings to change the battery. A total of three fully charged batteries were used. Recording with 85% image overlap lasted about 37 min with one battery change. The third recording with 80% overlap was done the following day, on Sunday, June 27, it lasted about 24 min with one battery change. The fourth and final recording, with 75% overlap, was done with a single battery charge for a total of 18 min.

The third and final research point (I-3) was recorded on Saturday, July 3, between 7:00 and 9:00 A.M. The procedure is identical to the second research point. Three flight plan models were adjusted using the PIX4Dcapture application. The first chosen flight plan method is "double grid recording" at a 50 m altitude.

The most optimal percentage of image overlap (85%) was chosen based on the results obtained from the second research point (II). The total flight time was 24 min with one battery change. Circular motion around the center of Medvedgrad was chosen for the second flight plan model. The flight altitude was set to 50 m. The flight lasted a little over 9 min.

Manual entry of "waypoints" via the DJI GO application was used for the final flight plan model (Fig. 3a). The flight altitude was 50 meters and it lasted a little over 15 min. After each recording session, the quality control of the taken image is performed. If some images do not meet the requirements in terms of brightness, contrast, sharpness, or exact position, these images are then not retaken.

Data Processing

After each recording activity is completed, the images from the microSD card (SanDisk Ultra 32GB) are transferred to the internal SSD on the MacBook Pro 2015 Retina. Abode Photoshop opens all the captured images saved in DNF (digital negative file), or raw files made of all the original media data and metadata. After checking the images and possible edits that were done (contrast, lighting, shadow), the images are saved in a separate folder in .jpg format. This format is compatible with 3D reconstruction software (PIX4Dmapper).

An additional step of cropping images is being done for research point one (I-1). In all images taken at a distance of more than 10, 20, 30 and 40 m, an image is cropped (Fig. 3b) in order to obtain a frame as similar as possible to the one taken from 10 m away. This way an identical surface in all the images is compared.

Data Analysis

The images were taken and edited in jpg. the format is entered into the PIX4Dmapper 3D reconstruction software. According to the defined research plan, there are 20 images entered in PIX4Dmapper under research point one (I-1). Together with twenty images, 45 images taken by the method of circular motion around the center of Medvedgrad are entered as well. These images serve as a reference for detecting 2D image key points. The first step in 3D reconstruction is locating the image's key points.

The obtained results (number of key points per image) are entered in a separate table for further analysis. It is not necessary to do the other 3D reconstruction steps for the first research point.

Edited images with only one image overlap setting are entered for the purpose of researching the second (I-2) point. For each of the four overlap settings, a 3D reconstruction is done, including a global point cloud. The requested data is the total number of 3D key points in the point cloud for each overlap setting separately. In research point three (I-3), a complete reconstruction of the computer model is done for each of the three flight plan models, which includes the surface texture for the visual display of the final result.

Research Problems and Hypotheses

The issue of aerial photogrammetry is mentioned in the fourth chapter of this study. It details the problems found by authors of scientific papers. It is an issue with a large range and this research project will test the hypotheses from several aerial photogrammetry workflows.

Influence of Increased Horizontal Distance of the Camera on the Number of Detected Key Points (Features) Per Image

Using digital or mobile device cameras, image quality depends on factors like weather conditions, sensor quality, stability, and distance. Increased distance from the subject typically results in decreased image quality, but advancements in sensor technology have extended the usable distance without significant quality loss. The unmanned aerial vehicle in this study has a 12-megapixel CMOS sensor mounted on a gimbal to minimize vibrations and ensure stable images. Previous research by Yanagi and Chikatsu (2016) has shown that increasing recording altitude improves overlap accuracy. This research aims to determine the maximum horizontal and vertical distance from the object without compromising quality. This is particularly challenging for tall objects that require multiple altitudes for complete coverage. By moving the aerial vehicle further from the subject and increasing altitude, a full frame can be achieved to capture the entire vertical portion of the object, eliminating the need for recording at higher altitudes.

Influence of Different Percentages in Image Overlap on the Total Number of 3D Key Points in the Global Point Cloud

Overlap in reconstruction software is crucial and relates directly to the number of detected key points in each image. Through triangulation, the system calculates the 3D position of key points based on image overlap, generating a global point cloud. Reducing the image overlap percentage from 90-85% or from 80-75% leads to fewer key point overlaps due to a smaller image area being analyzed. However, increasing camera resolution decreases the number of detected key points per image. Studies suggest that a 90% overlap yields better results than an 80% overlap, with a recommended overlap range of 80-90%. Another perspective suggests minimum overlaps between 70 and 80%. This research will test four overlap ratios: 90, 80, 70 and 60%.

Influence of Unmanned Aerial Vehicle Flight Plans on the Total Number of 3D Key Points in the Global Point Cloud

Flight plans are tailored to the desired image overlap. The double grid plan captures the widest surface, resulting in a larger number of images and a more precise point cloud due to increased overlap. On the other hand, circular motion around the center provides a faster flight time but neglects the interior of Medvedgrad, leading to fewer 3D key points in the middle of the point cloud. The author's hybrid flight plan combines the advantages of both methods, aiming to maintain the total number of 3D key points while reducing flight time. Commercial software offers predefined flight plans: Double grid and circular motion. However, these plans are not ideal for the elongated, rectangular shape of Medvedgrad. The hybrid approach is designed based on the building's unique geometry. The research will evaluate the number of detected 3D key points and total flight time. Three hypotheses emerge from these considerations:

Hypothesis 1: Increasing the horizontal distance will not reduce (<5%) 2D key points per image
Hypothesis 2: The total number of 3D point cloud key points will decrease as the percentage of overlap decreases
Hypothesis 3: The hybrid (author’s) flight plan will result in a similar total number (<5%) of 3D key points in the global point cloud as well as the double grid flight plan, with total shorter flight time. The circular motion flight plan will produce the smallest number of 3D key points

Results

The research results were conducted using PIX4Dmapper computer software, a Mac-Book Pro 2015 laptop computer with an Intel Corei7-5557U 3.10 GHz processor and 16 GM of RAM. As PIX4Dmapper is not compatible with MacOS, Windows 10 Home, a 64-bit operating system, is installed via the Boot Camp application.

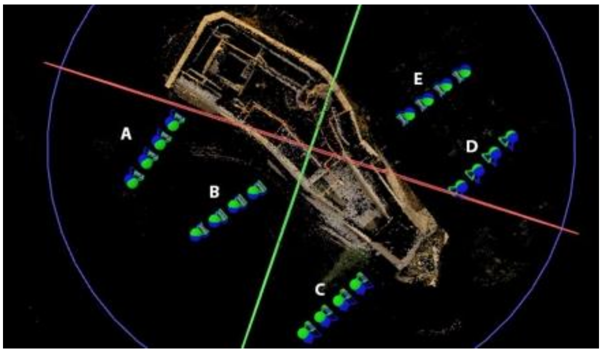
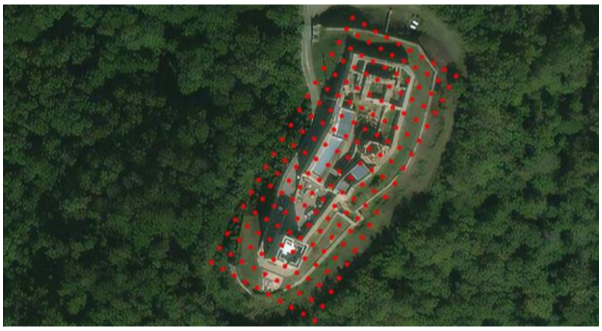


Fig. 4: Exact recording position



(a)

(b)

Fig. 5: (a) Overview of recording positions for 90% overlap; (b) Point cloud with 90% overlap

Data analysis was divided into three subcategories, according to each research point.

Results of Research Problem I-1

The research was conducted at five locations marked with letters from A. At each location, the recording was done from four different distances from the subject (10, 20, 30 and 40 m). Figure 4 shows all recorded positions, set in the local coordinate system in PIX4Dmapper, via input GNSS geographic coordinates.

Key points were analyzed at various distances from different positions. From position "A", 16,573 key points were found at a 10 m distance, decreasing to 14,167 key points at 40 m. Position "B" yielded 25,897 key points at 10 m and 21,894 key points at 40 m. Position "C" had 16,433 key points at 10 m and 14,229 key points at 40 m. Position "D" detected 12,161 key points at 10 m and 9,991 key points at 40 m. Lastly, position "E" found 8,975 key points at 10 m and 7,367 key points at 40 m. Descriptive analysis was conducted to group the results based on distance, resulting in five values for each distance and calculating the arithmetic mean separately to reduce deviations based on position.

Results of Research Problem I-2

The research of this research point is the total number of 3D key points in the global point cloud, the number of 2D key points, the number of images, and the total flight time displayed in minutes. A double grid was used for the flight plan. Four image overlap settings were captured separately: 90, 85, 80 and 75%.

The flight plan for 90 percent image overlap consisted of a grid of ten cross points and 19 longitudinal recorded points. The total flight time was 64 min and 55 sec with two battery changes (three sets of batteries in total). There were 190 images taken. The global point cloud consisted of 3,197,173 3D key points (Fig. 5a). The total number of 2D key points on all the images amounted to 7,626,333.

The research results include the total number of 3D key points, 2D key points, images, and flight time. The flight plan used was the double grid, with four separate image overlap settings: 90, 85, 80 and 75%.

For 90% image overlap, the flight plan had ten cross points and 19 longitudinal recorded points, totaling a flight time of 64 min and 55 sec. A total of 190 images were captured, resulting in 3,197,173 3D key points and 7,626,333 2D key points (Fig. 5b).

The 85% image overlap flight plan had seven cross points and 13 longitudinal recorded points. The flight time with one battery charge was 35 min and 23 sec, capturing 91 images. There were 3,175,122 3D key points and 3,652,612 2D key points.

With 80% image overlap, the flight plan included six cross points and ten longitudinal recorded points. The flight time was 23 min and 21 sec, capturing 60 images. There were 2,246,373 3D key points and 2,408,345 2D key points.

The final flight plan with 75% image overlap had five cross points and nine longitudinal recorded points. The flight time without battery changes was 17 min and 49 sec, capturing 45 images. There were 1,714,922 3D key points and 1,727,122 2D key points.

Results of Research Problem I-3

The most optimal result (85% image overlap) from the previous research point (I-2) was used for a double grid. The number of 3D key points in the previous research amounts to 3,175,122. There were 91 images collected in a period of 35 min and 23 sec.

Fig. 6: Circular (a) Hybrid; (b) Flight plan

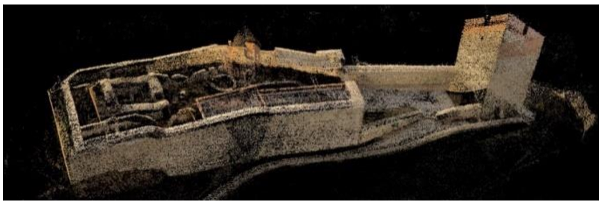


Fig. 7: Point cloud created by a circular flight plan

The circular motion around the center of Medvedgrad was also set at 85% image overlap Fig. 6. The recording altitude amounted to 50 m. The flight time was 9 min and 4 sec and 38 images were taken.

The author's hybrid flight plan took 21 min and 45 sec. There were 57 images taken. The total number of detected 3D key points amounts to 3,171,856 Fig. 7.

Vertical height in relation to the ground is 15 m, twice as low as the highest point of the subject captured. A reference sample must be taken before taking 20 images. The chosen recording method is circular motion around the center of the subject with 90% image overlap at 50 m altitude. An image taken from a distance of 10 m is considered to be a base image. Since recording from a greater distance covers a larger frame, Adobe Photoshop was used for additional image editing.

In all images taken at a distance of more than 10 m, an image is cropped in order to obtain a frame as similar as possible to the one taken from 10 m away. This additional process allows measurement of the same surface and provides more representative results. The images are imported into the PIX4Dmapper 3D reconstruction software in .jpg format. According to the defined research plan 20 images were entered. Together with twenty images, 45 images taken by the method of circular movement around the center of Medvedgrad are entered as well.

The second research problem used precision recording using the PIX4Dcapture mobile application. All flight parameters are set in the program, including the percentage of image overlap. Four image overlap settings were captured separately: 90, 85, 80 and 75%. The grid flight method was chosen since this recording method requires the highest number of images that result in the most accurate results. The unmanned aerial vehicle was taking images from a 50 m altitude. A 3D reconstruction of the global point cloud is done for each of the four image overlap settings. The requested data is the total number of 3D key points in the point cloud for each overlap setting separately. The total number of 3D key points on the global point cloud is analyzed in relation to the percentage of image overlaps.

The procedure for the third research point follows the methodology of the previous point. Three flight plan models were adjusted using the PIX4Dcapture application. The first chosen flight plan method is "double grid recording" at an altitude of 50 m with 85% image overlap.

The results of the research were conducted using PIX4Dmapper computer software and a MacBook Pro 2015 Retina laptop. Data analysis is divided into four subcategories, according to each research point, as well as the dimensional analysis of the completed 3D model.

Descriptive analysis was used to analyze the gained research results. In order to get the representative data, it is necessary to group the results according to the distance from the research subject. That resulted in five values for each distance. In order to eliminate larger deviations depending on the position, the arithmetic mean for each distance will be calculated separately. The mean value (Table 1) for each measurement point is obtained this way.

The results of this second research point are the total number of 3D key points in the global point cloud, the number of 2D key points, the number of images, and the total flight time displayed in minutes. A double grid was used for the flight plan. Four image overlap settings were captured separately: 90, 85, 80, and 75%. All four parameter overlap results are shown in Table 2.

Table 1: An overview of mean value for 2D key points at all five positions

Distance (m)	2D key points
10	20,009.75
20	19,820.50
30	19,300.75
40	16,912.00

Table 2: An overview of mean value for 2D key points at all five positions

Image overlap %	3D key points
90	3,197,173
85	3,175,122
80	2,246,373
75	1,714,922

Table 3: An overview of the total number of 3D key points using different recording methods

Flight plan	3D key points	Flight time
Double grid	3175122	35 min 23 s
Circular	1621562	9 min 4 s
Hybrid	3171856	16 min 22 s

Table 4: Dimensional deviation on all three flight plans dimensional analysis

	Double grid [m]	Circular [m]	Hybrid [m]
X-axis	0.35	0.45	0.36
Y axis	0.39	0.42	0.40
Z axis	0.51	0.53	0.51
Average	0.42	0.47	0.42

Three flying methods (flight plans) were researched. Two are predefined in PIX4DCapture mobile application and the third one was created by the authors. The results are shown in Table 2. The result from the previous research point was taken for the grid flight plan. The total number of detected 3D key points in the point cloud amounts to 3,175,122. There were 91 images collected in a time period of 35 min and 23 sec.

Another recording method is circular motion around the center of the subject with 85 percent image overlap. The recording altitude amounted to 50 m. The flight time was 9 min and 4 sec and 38 images were taken. The total number of detected 3D key points amounts to 1,621,562.

The author’s hybrid flight plan lasted 21 min and 45 sec. There were 57 images taken. The total number of detected 3D key points amounts to 3,171,856.

Dimensional Deviations of a 3D Computer Model

The final step is a complete computer model 3D reconstruction for all three flight methods. Table 3 shows the results for all three flight plans. PIX4Dmapper software has settings with the highest resolution and detail. Double grid was the first flight plan for which 3D reconstruction was done. Due to this method, 91 images were collected creating 3,175,122 3D key points in the global point cloud. The total time of 3D reconstruction was 7 h and 12 min. In the obtained model, the deviation of the transverse axis is 35 cm, longitudinal 39 cm and the altitude deviation is 0.51 cm.

The second reconstructed 3D computer model was a circular motion model around the center of the subject recorded. This flight plan did not include flights over the subject of the recording but only recording from the side. There were 38 images collected, which created a global point cloud with 1,621,562 3D key points. 3D reconstruction time was 3 h exactly. Table 4 shows that the recorded transverse dimensional deviation is 45 cm, longitudinal 42 cm, and vertical deviation 53 cm.

The third three-dimensional reconstruction was the author’s hybrid flight plan. Due to this method 57 images were collected creating 3,171,856 3D key points in the global point cloud. The deviation of the transverse axis amounts to 36 cm, longitudinal 40 cm and the altitude deviation is 51 cm. The total time of reconstruction was 4 h and 45 min.

Discussion

Results in I-1 show a decrease in detected 2D key points per image with increasing distance from the captured object. Moving from a 10 m distance to 20 m only results in a negligible 0.01% loss of key points. However, at 30 m, there is a 3.6% loss and at 40 m, the loss is 15.5% Fig. 8. This indicates that the equipment's limit, specifically the camera sensor, is around 30 m. Recording at a horizontal distance is the maximum limit without significant deviation (<3.5%) from the initial value (10 m).

In I-2, four types of image overlap were measured. The global point cloud captured with 90 and 85% overlap showed a similar number of 3D key points, with a difference of only 0.7% and an accuracy of 0.2 key points. However, recording at 85% overlap was 45% shorter than at 90% overlap. With an 80% overlap, there was a 30% reduction in 3D key points and an accuracy of just over 0.6 key points. As expected, the worst results were obtained at 75% overlap, with a 46.4% reduction compared to 90% overlap Fig. 9. Based on these results, 85% overlap is considered the optimal choice.

Regarding different flight plans, the double grid and the author's hybrid plan showed a similar number of 3D key points in the global point cloud. The circular motion plan had the worst results with 49% fewer 3D key points. The author's hybrid plan also had a 9 min advantage in flight time compared to the double grid plan.

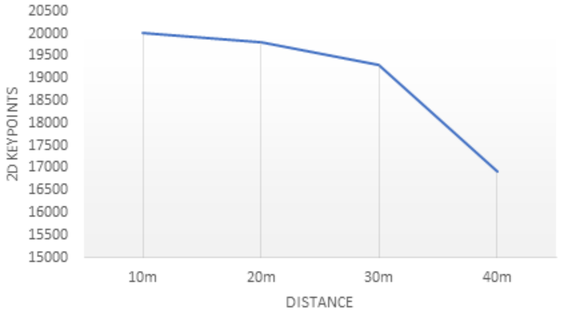


Fig. 8: Overview of the mean value of 2D key points for all five positions

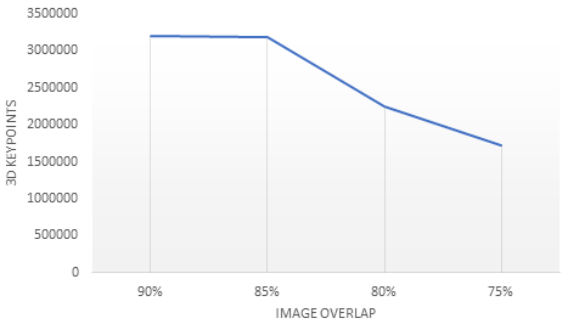


Fig. 9: Overview of the mean value of 2D key points for all five positions

The final analysis of 3D computer model reconstruction revealed dimensional errors. The total error, considering all three axes, was 42 centimeters for both the double grid and the author's hybrid plan. The circular motion plan had a slightly larger error of 47 cm due to limited coverage. Based on these results, the author's flight plan offers a more optimal and economical approach to data collection:

Hypothesis 1: States that increasing horizontal distance will not drastically reduce (<5%) 2D key points per image. The first research point shows a drop of only 700 key points (3.6%) when moving from ten to 30 m. However, at 40 m, there is a significant drop of 15.5% in 2D key points, which would result in a loss of 3D point cloud key points. Thus, the accepted threshold for H_1 is 30 m

Hypothesis 2: States that the total number of 3D key points will decrease as the overlap percentage decreases. Measurements with four image overlap settings confirm H_2, with a gradual reduction in 3D key points as the overlap decreases

Hypothesis 3: Compares the hybrid (author's) flight plan, double grid flight plan, and circular movement flight plan. The author's hybrid plan and double grid plan resulted in a similar total number (<5%) of 3D key points in the global point cloud, but the author's hybrid plan had a shorter flight time. The circular motion method produced the fewest 3D key points but was the fastest. Therefore, H_3 is entirely confirmed

Conclusion

Photogrammetry is a complex technique consisting of several specific and complicated activities. Although they seem to be separate, the whole process is in fact a type of cascade reaction. If the data recording, being one of the first activities in photogrammetry, is not well done, all the processes that follow will struggle to get the right result. If a new media, in the form of an unmanned aerial vehicle, is included in that technology mix, the complexity of proper handling of this technology increases.

Standardization is the basic segment of any industry that provides reliable, constant, and controlled results. Up to date, there is no such thing in the sphere of aerial photogrammetry. One of the primary reasons is the fact that this is still a relatively new technology. This study tries to give an answer to the optimization of data-collecting activities. It should be noted that the obtained results are in direct correlation with the equipment used. DJI Phantom 3 Standard unmanned aerial vehicle was used during the entire research. It is key to emphasize this point since repeating this research by using different equipment could result in a different set of results and conclusions.

Several elements need to be determined before starting to record a certain subject or terrain. This refers to the flight plan, i.e., a method we want to use for collecting images in order to get quantitative and qualitative results. Quantitative refers to the image frequency which is expressed in the percentage of image overlap and it is at the same time the basic technique for 3D reconstruction. The image resolution is sufficient for a qualitative result so that the software can perform the most precise reconstruction possible. This all means that for collecting images a good flight plan needs to be chosen, and an appropriate percentage of image overlap needs to meet the good quality standard. In the case of aerial photogrammetry, this is determined by distance and flight altitude. These three elements that were the topic of this research determined the optimal settings and work methods.

The results of this study are presented in line with the hypotheses. It could have been assumed that by distancing of the unmanned aerial vehicle from the subject of the recording there would be a drop in the number of 2D key points. However, the analysis determined the threshold at which a measurable drop in 2D key points occurs. Based on that a 30-meter maximum horizontal distance that could be used for taking images, without the loss of a measurable number of 2D key points, was determined. Once the total number of 3D key points was obtained, the threshold for image overlap was also determined. The analysis determined a significant drop of 3D key points between 85 and 80% of image overlap.

The last research point concerned flight plans, i.e., methods of field coverage. Two redefined field plans were used that can be found on almost all applications for unmanned aerial vehicles. The results showed that the double gris gave far better results than the circular motion which is not surprising since the circular motion does not cover the central part of the subject. This is especially emphasized when capturing larger dimension subjects, as was the case in this research. The negative side of this method is flight time. Considering the average maximum battery life in an unmanned aerial vehicle is around 20 min, recording which requires two to three additional batteries is not optimal. For this reason, a flight plan was created which is a combination of the existing predefined plans. The analysis of the obtained results shows that the hybrid method of recording results in almost the same number of 3D key points as the double grid flight plan. However, the time that was needed for the unmanned aerial vehicle to be in the air while performing the author's flight plan was twice as short compared to other flights.

Based on this research several guidelines could be determined for a more optimal use of Phantom 3 Standard aircraft:

- Maximum distance from the subject of the recording amounts to 30 m
- Recording should be done with 85% image overlap
- A specialized flight plan should be created based on the geometry of the recorded subject

It should be pointed out that the 3D computer models that were reconstructed in this research are still not ready to be directly uploaded into a "gaming engine" or other similar programs. All three models show great visual disadvantages that need to be corrected using the specialized 3D manipulation software. This technology is already today largely applied across different industries. With the unstoppable daily developments of hardware and software, its application and availability will continue to grow.

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Author's Contributions

Boris Tunjić: Conceptualization, methodology formal analysis, investigation, written original drafted preparation.

Andrija Bernik: Written and reviewed and edited, supervised, and funded.

Andrej Čep: Written reviewed and edited.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved. The authors declare no conflict of interest.

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