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Optimising UAV Data Acquisition and Processing for Photogrammetry: A Review

Abstract: Unmanned aerial vehicles (UAVs) are used to acquire measurement data for an increasing number of applications. Photogrammetric studies based on UAV data, thanks to the significant development of computer vision techniques, photogrammetry, and equipment miniaturization, allow sufficient accuracy for many engineering and non-engineering applications to be achieved. In addition to accuracy, development time and cost of data acquisition and processing are also important issues. The aim of this paper is to present potential limitations in the use of UAVs to acquire measurement data and to present measurement and processing techniques affecting the optimisation of work both in terms of accuracy and economy. Issues related to the type of drones used (multi-rotor, fixed-wing), type of shutter in the camera (rolling shutter, global shutter), camera calibration method (pre-calibration, self-calibration), georeferencing method (direct, indirect), technique of measuring the external images orientation parameters (RTK, PPK, PPP), flight design methods and the type of software used were analysed.

Keywords: photogrammetry, UAV, optimising, bundle adjustment, structure from motion

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1. Introduction

The use of unmanned aerial vehicles (UAVs) to acquire measurement data has recently become very common. This method is increasingly chosen for a wide variety of applications, including mining [1–3], inventory and design of engineering structures [4–6], forestry [7–9], damage detection and characterisation [10, 11], archaeology [12, 13] or cadastre [14, 15]. The multiplicity of UAV applications is rooted in the wide range of installed measurement sensors. UAVs can be equipped with vision sensors with different spectral characteristics, ranging from traditional RGB cameras, through multi- and hyperspectral cameras to thermal cameras. Unmanned systems equipped with LiDAR are also available [16].

Significant technological and research development in the field of unmanned platforms allows the attainment of greater accuracy and resolution of photogrammetric studies. Their use can form a partial alternative to traditional measurement methods or flights using manned aerial platforms. At the same time, the use of UAVs creates completely new opportunities in many aspects, for example, obtaining data in contaminated areas or areas inaccessible to traditional measurement devices [17–20].

Achieving the required measurement accuracy is a key factor in the case of photogrammetric studies. At the same time, from the practical and economic point of view, it is also important to take care of limiting the time and cost of works. Therefore, it is necessary to balance these factors and to strive for optimal solutions. Economic factors include the cost of equipment (type of UAV used, quality of cameras, their resolution and shutter type, measurement accuracy of GNSS modules used), cost and time of work (taking pictures from a lower ceiling increasing the accuracy but at the same time increasing the number of pictures required for processing and time needed to carry out the flight, the need to measure the ground control points (GCPs) in the field and in the pictures) and others (service costs, software costs).

The publication aims to present the achievements of UAV data acquisition and processing, related to optimizing the time and cost of work while taking care of the final accuracy of the studies. The paper focuses on aspects such as types of UAVs used, types of shutters used in non-metric cameras, calibration methods, georeferencing methods, mission planning methods and types of photogrammetric software used.

1.1. Limitations of UAV Systems

The low kerb weight of drones makes their performance very limited and also dependent on weather conditions. Temperature, wind speed and precipitation have been shown to have a very negative impact on battery life, controllability, aerodynamics, visibility, endurance, and even sensors designed to automatically respond when an obstacle is encountered. Unfortunately, despite increasingly accurate weather forecast models, the issue of precisely determining conditions at the time of a raid, especially if planned in advance, is difficult to resolve. This greatly limits the number of days on which measurements can be carried out safely and with the required precision [21, 22].

The main problem with unmanned aerial systems (UAS), is the limited battery life. Multi-rotor consumer-grade drones, very often used in photogrammetry due to their low cost, can spend a maximum of about half an hour in the air. Higher performance in terms of flight time can be definitely achieved using fixed-wing airframes [23]. Moreover, the working time itself or the battery life are highly dependent on the ambient temperature or the weight of the craft (higher weight is implies with increasing the power of the engines). Technological development enabling the application of more and more advanced solutions allows for the gradual extension of the flight time achievable on a single battery charge [24]. The need to acquire data for the long mission with simultaneous control of battery consumption, requires the ability from the operator to properly plan the mission, taking into account the risk possible due to external factors, such as the variability of weather conditions [25].

It also involves reducing platform load, which is a huge challenge for component manufacturers. Cameras and GPS and IMU modules used on unmanned platforms must fulfil specific weight and size criteria. This leads to the need for miniaturisation of components while ensuring the best possible parameters. This procedure is under rapid development, however consumer-grade drones are still fitted with GNSS navigation modules that determine position with metre accuracy, while drones with centimetre-accuracy receivers are about 5–6 times more expensive. An alternative, or relatively a supplementation, to the measurement of exterior orientation parameters (EOP) is the use of ground control points measured in the field. A good practice is to use check points, which field coordinates are not used in block alignment but taken into account during accuracy assessment [26]. However, the application of such a solution requires time-consuming field measurements with care for the highest possible accuracy of determining the position of the points. Investment in time and human resources is associated with generating additional costs [27].

1.2. Optimisation

The topic of optimisation of UAV data acquisition and processing is appearing with greater frequency in the literature. Issues related to the assessment of the accuracy of studies [12, 28], EOP measurement method [29, 30], UAV flight trajectory planning [31, 32], GCPs measurement method and deployment [26, 33] and the software or algorithms used [34, 35] are analysed. Limitations in the use of drones make it an important issue for researchers to strive to fulfil the accuracy requirements for photogrammetric products, while minimising the time and cost of data acquisition and processing work. It is also very important to ensure that the measurements made are repeatable because achieving the required accuracy once does not prove the quality of the method [36–38].

2. Types of Drones and Cameras

2.1. Type of UAV Used

Various criteria can be used to classify UAVs. These mainly include weight, flight range, and design type [39]. UAVs of two basic types, namely fixed-wing and multi-rotor (Fig. 1), are used for measurement purposes. Each year, new models occur in the offer of drone manufacturers. This demonstrates the growing demand for both fixed-wing and multi-rotors, and the decision to choose a particular model depends on many practical as well as economic factors [40].

a) b)

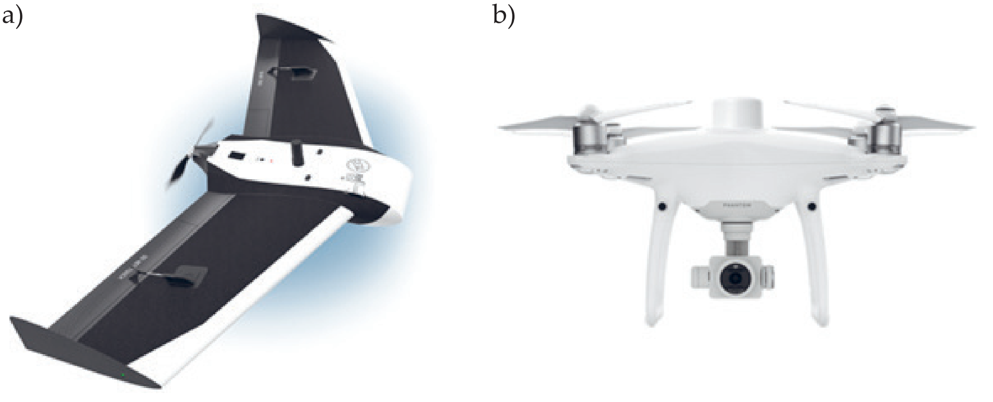

Fig. 1. An example of fixed-wing (a) and multi-rotor (b) drones
Source: https://www.flytechuav.pl/ and https://dji-ars.pl/ (access: 8 November 2022)

Multi-rotor UAVs are characterised by their ease of use. They enable stable flight as well as take-off and landing in practically any place, even with little available space. Due to their ability to hover in the air and reach places inaccessible to traditional ground measurements, they allow photography for both mapping and inventory of engineering structures. Fixed-wing UAVs require much more skill from the operator. After taking-off, it is not possible to stop the drone in place and therefore they are mainly used for large area mapping purposes. Due to their much higher cruising speeds, they can cover a much larger area with the same battery life. Landing with this type of drone can only be performed in open spaces. To alleviate this problem, a fixed-wing drone equipped with an additional vertical take-off and landing (VTOL) system can be used, for example, the UAV BIRDIE VTOL produced by FlyTech or WingtraOne produced by Wingtra. However, additional elements in the form of propellers increase the weight of the equipment which translates into higher battery consumption [23, 41].

Market research has shown that fixed-wing UAVs are relatively more expensive. However, the potential to cover an area up to 10 times larger in one flight in comparison with one performed by a multi-rotor drone positively affects the final development time and costs of field work. Literature studies show that both multi-rotor [33, 42, 43] and fixed-wing [44–46] drones are used for measurement purposes, and the achieved accuracies can reach centimetre levels. For example, in the publication [27], multiple alignment variants of images acquired with a fixed-wing FENIX UAV were analysed. The results obtained in the accuracy analysis are about 5 cm RMSE 3D in the best variant. Similar centimetre level results were obtained in the publication [28] with a fixed-wing Birdie UAV and in [47] with a fixed-wing senseFly eBee RTK UAV. For comparison, in the research [48], a multi-rotor DJI Mavic Pro UAV was used and centimetre accuracy was also obtained (about 4 cm RMSE in XY and 5 cm RMSE in Z in the best variant). Similar centimetre level results were obtained in the publication [49] with a multi-rotor DJI Phantom 4 Pro UAV. The choice of a particular type of UAV depends on the type of work planned, the scope of the study, or economic factors (Tab. 1).

In the research [23] it was attempted to compare the studies for environmental purposes performed on the basis of data from fixed-wing and multi-rotor drones. It was shown that satisfactory assessments of environmental impacts can be performed on the basis of products obtained using data from both types of UAV. Some differences were also noted. The data acquired with the multi-rotor was more precise and detailed, so such a drone would be better suited for projects requiring higher accuracies. In contrast, in terms of optimisation and taking into account factors such as cost, maintenance and flight time, the fixed-wing UAVs provide greater benefits.

Similar conclusions were drawn in studies [39], where a comparison of products and final accuracies obtained for the same study area was analysed using data acquired from a multi-rotor drone (DJI Phantom 4 Advanced) and a fixed-wing drone (eBee Classic). For the accuracy analysis performed based on 15 check points, the multi-rotor drone (RMSE X: 0.31 m, RMSE Y: 0.12 m, RMSE Z: 0.14 m) performed slightly better than the fixed-wing (RMSE X: 0.34 m, RMSE Y: 0.14 m, RMSE Z: 0.23 m), especially in the vertical plane. The visual evaluation of the products showed that more detailed studies could be performed using the multi-rotor drone. The conclusion that it is better to use a UAV of this type for smaller areas was confirmed.

A comparison of fixed-wing and multi-rotor UAVs was also conducted in 2013 on the example of slope mapping [41]. Comparisons were made between the obtained accuracies and photogrammetric products such as digital elevation model and digital orthophoto. The errors obtained by the researchers were at a significantly higher level than those currently achieved (sub-meter level). However, the conclusions drawn from the comparison of the two types of UAVs are similar to those today. Multi rotor UAV allowed higher accuracies to be achieved, while fixed-wings are better employed to cover a significantly larger area. Its cost, however, was definitely higher. Results obtained a few years back show that the final accuracies obtained are improving, while the comparison of both types of UAVs is still based on similar conclusions.

The study [50] compared three unmanned platforms: a heavy-lift hexrotor platform, a small quadrotor platform, and a fixed-wing platform. The obtained 3D reconstruction of the motorway section was analysed. It was shown that the factor with the greatest influence on both accuracy and resolution of the resulting reconstruction was the camera resolution. However, it was observed that the choice of platform also influenced the resolution of the point cloud. The use of a multi-rotor platform with sensor stabilization increased the point resolution by 16% compared to the fixed-wing platform.

The study [51] compared two models of multirotor UAVs (Parrot Anafi and DJI Mavic Pro 2) without RTK-GPS and one model of fixed-wing UAV (SenseFly eBee-Plus) with RTK-GPS for observing snowpack evolution in mountain areas. The results obtained were related to TLS and showed that the quality of the snow maps was very similar. All of the tested UAVs provided high quality snow depth maps (RMSE lower than 0.22 m). At the same time, it was noted that fixed-wing UAVs are much more efficient in larger areas. However, they do not allow landing in all conditions. In this respect, multi-rotor UAVs are definitely more flexible and safer. This is especially important in mountain areas with varied topography. Multi-rotors are also more compact and smaller, making them easier to transport.

A comparison of fixed-wing and multi-rotor drones is providing in Table 1.

Table 1. Comparison of fixed-wing and multi-rotor drones

Type of drone	Advantages	Disadvantages
Multi-rotor	– simplicity of use – compactness – possibility of hanging in the air – the possibility of taking off and landing anywhere – wide range of applications – lower price	– low flight speeds – shorter spatial range
Fixed-wing	– higher cruising speeds – the ability to cover a much larger area at the same time – greater flight stability	– the need to take off and land in an open space – more difficult to use – higher price

2.2. Types of Shutter Used

One of the most important elements of a camera which affects the geometry of the image is the shutter. There are two types of shutters: global shutter (GS) and rolling shutter (RS). Due to the much lower price, the majority of consumer-grade cameras and drone cameras are equipped with a RS. They differ from GS in that the frame surface is not exposed evenly, but progressively line by line. This translates into a distortion of the geometry of the images, especially if they are taken in motion [52].

When capturing photographs with UAVs, it is not possible to completely avoid relocating. For multi-rotor drones it is possible to hover in place for the duration of the time required to take a particular photograph but for fixed-wings this is not possible. Errors can be compensated for by decreasing the cruising speed and adjusting it to the shutter speed time. However, this has the effect of significantly reducing the spatial range that will be imaged, taking into account the same battery life [53]. The study [54] found that flight configuration does not improve errors induced by the use of the RS.

To mitigate the disadvantages of using RS, the techniques to model and correct the distortion resulting from their use were developed. The studies [53] show that to achieve an accuracy of about 1–2 ground sample distance (GSD) in the X/Y direction and 2–3 GSD in the Z direction when using an RS, the cruising speed must be significantly reduced. Depending on the reading time of the equipment used, the upper limit is 4–8 m/s. Simultaneously, the same study shows that by using RS distortion modelling it is also possible to achieve the required accuracies for higher cruising speeds. The final errors obtained are not higher than those obtained on the basis of photographs taken with the GS. However, they show that the use of much cheaper consumer-grade equipment with RS makes it possible to obtain the required accuracies and use them in map studies.

In research [55], a two-step rolling shutter effect correction method was proposed and implemented in the MicMac free photogrammetric software. It was shown that the used method allows to improve the accuracy of studies in the range of 30–60% for a block configuration and 15–25% for a corridor configuration. The results obtained were compared with the results achieved using RS correction methods available in commercial programs (Agisoft Metashape and Pix4D). The comparison showed that for block configurations the final results (error values) are comparable, while for corridor configurations the method proposed by the authors is definitely more accurate.

The use of cameras equipped with RS (Sony a6000) and GS (Sony RX1R II) was also analysed [27]. It showed that the use of distortion modelling for the RS allows accuracies to be obtained that are similar to those from a global shutter camera. The same cameras were also used in [46]. It was confirmed that despite the use of different shutter types, similar final accuracies could be achieved when RS distortion modelling is used.

An analysis of the accuracy of variants made with and without the use of RS distortion modelling is presented in research [56]. Variants with different flight speeds (8 m/s and 12 m/s) were performed. It was shown that the use of distortion modelling improves the accuracy from 6.33 cm to 4.78 cm at 8 m/s and from 7.01 cm to 4.0 cm at 12 m/s.

A comparison of rolling and global shutters is provided in Table 2.

Table 2. Comparison of rolling and global shutters

Type of drone	Advantages	Disadvantages
Rolling shutter	– greater availability – lower price	– the need for additional rolling shutter effect correction
Global shutter	– no need for additional corrections	– higher price – reduced availability

2.3. Camera Calibration

The vision sensors installed on board UAVs are predominantly non-metric digital cameras. Due to their low price and structure low resistance resulting from the need to reduce weight, they are characterised by an instability of interior orientation parameters (IOP). Therefore, camera calibration can be crucial to achieve adequate accuracies. As the IOP of consumer-grade cameras can exhibit instability which is significant for processing results, it can be necessary to repeat calibrations or even calibrate the camera independently for each flight. This increases the work time and requires access to the calibration infrastructure. UAV cameras are focused for very long distances and short exposure times are required to minimise blurring. Due to the resulting shallow depth of field, it is not possible to use the same settings for different flight heights. Calibration with these settings also requires a large test field so as to ensure that the calibration marks are properly focused. This results in a need to provide a considerable amount of space and increases the workload as a result of the necessity of preparing a suitable test infrastructure. Therefore, in the case of UAV-based studies, the IOP are estimated along with other parameters in the bundle adjustment. The IOP in such cases are up-to-date at the time of the flight. However, this approach can generate errors, especially in vertical coordinates. For the proper implementation of self-calibration it is necessary to provide appropriate geometric configurations of the photograph block, including a sufficient number of ground control points to guarantee the determinability of calibration parameters. This can be critical in the case of blocks of photographs with small depth [57–60]. In the self-calibration procedure, the geometry of the bundle block can be strengthened by the inclusion of oblique images for multi-rotor UAVs or flying cross strips at a different elevation for fixed-wing UAV [61–63]. This reduces the projective coupling between interior and exterior orientation parameters [47].

Research [64, 65] additionally shows that the use of uncompressed RAW images is recommended for the pre-calibration process. The result of calibration carried out on compressed images, for example JPG, may be significantly error. Unfortunately, most cameras require considerably more time to acquire and save an image in RAW format. This can be problematic for flights with large forward overlaps when the velocity of the UAV cannot be adequately reduced.

The effect of pre-calibration on final accuracies of the BA achieved with the application of the non-metric camera installed on board the UAV and a three-dimensional test field was analysed in the studies [66]. Data for calibration were acquired at three different cruising altitudes (23, 28, 35 m) with a variable number of GCP (3, 14, 50, 100). The results were compared with studies conducted with self-calibration. It was shown that the use of parameters from pre-calibration increases the accuracy of studies by about 50% when using a large number of GCP and by more than 75% when using a small number of GCP. The analyses show that the use of pre-calibration has a greater impact on studies using a small amount of input data, for example when measuring a significant number of GCP would be impossible or dangerous.

A comparison of self-calibration and pre-calibration was also performed in [67]. The researchers evaluated a test field-based calibration for DJI Phantom 4 Pro and Parrot Anafi UAVs. The results were generated on the basis of the block alignment based on the determined parameters, in addition, various flight altitudes were analysed. The results show that calibration made with test fields gave higher RMSE than self-calibration for both UAVs. This is not consistent with the results presented in [66]. However, the calibration test fields in this study were significantly smaller than in [66].

The method of pre-calibration and self-calibration with varying number (5, 13) and accuracy (σ = 22, 2 and 0 mm) of GCPs was compared in the study [58]. The variants with oblique photographs were also taken into account. It was shown that using a higher number of more accurate GCPs, without the inclusion of oblique photographs, the final results obtained with the application of the pre-calibration and self-calibration were similar. The inclusion of oblique photographs in the alignment resulted in increased accuracy of horizontal coordinates for the self-calibration solutions but the error in vertical coordinates remained similar for both methods. Using less accurate ground measurements and additional oblique photographs, slightly more accurate results were obtained for the variants with self-calibration. Due to the costliness of pre-calibration, self-calibration is a better option and achieves a similar degree of accuracy to pre-calibration. However, it requires a sufficiently strong photograph configuration and a large number of GCPs.

The self-calibration process is highly dependent on the image configuration. Consequently, corridor mapping is particularly error-prone. With this configuration, images are taken in series, and including additional cross flights or more strips is not cost-effective. Also for areas with low topographic diversity, a correlation between IOP and EOP is generated. This translates into the occurrence of a bowl effect [63, 68]. In another study [69], it was shown that elimination of the bowl effect can be achieved by densifying the distribution of GCPs. However, this increases the time required for fieldwork and it is therefore more beneficial to include oblique images. The topic of calibration in corridor mapping was also analysed in [70]. The results show that in conditions where redundancy and ground control are limited, calibration should be performed in configurations such as production, it should be possible to re-estimate parameters in bundle adjustment, the preferred model for lenses with a predominant radial distortion component is the Brown model and the number of calibration parameters should be reduced.

3. Georeferencing Methods

The adjustment of a block of photographs using only the observation of image coordinates is only possible within an arbitrary scale, position, and angular orientation. Meanwhile, the photogrammetric products require representation in an appropriate, metric coordinate system, sometimes in a state system. This requires the block of photographs to be georeferenced. This is achieved by using GCPs or by measuring elements of exterior orientation – typically coordinates and sometimes angles. Both methods can be used together. Georeferencing not only removes scale, position and orientation defects but also improves adjustment accuracy. GCPs not included in the alignment form the basis for independent accuracy assessment – they are used as check points [71]. A number of studies were carried out to test the best possible configurations for the use of GCPs. Issues concerning their optimal number and position have also been analysed [26, 33, 42, 72, 73].

The studies [33] revealed that the increasing the number of GCPs up to some value improves accuracy and any further increase only brings minor improvements. In addition to the number of points, the configuration of their placement has a strong impact on the results. Of the five GCPs placement configurations used (edge, central, corner, stratified, random), the best results of 0.035 m read on the check points (CPs) in the RMSE XY range were obtained when the GCPs were placed at the edges of the study area, while in case of RMSE Z range of 0.047 m were obtained with the stratified placement. The conclusion to be drawn is that in order to obtain the highest possible accuracies, it would be the best to arrange the GCPs around the edges and complete the interior of the area with a stratified arrangement. Similar conclusions were reached in the study [74]. It was found that both the number and distribution of GCPs affect the final accuracy. The results show that for optimal planimetric results GCPs should be located at the edges of the area, while for optimal altimetric results GCPs should also be placed in the centre of the area.

The study [75] aimed to find the best variant for the distribution of 3 GCPs for a slope area of 1 ha. The weakest variants were considered to be those in which the GCPs were placed at the bottom of the slope. Placing the GCPs in the top part of the slope significantly reduces the final errors. In the best variant, where GCPs were both at the bottom and at the top (forming a triangle with vertex in the centre of the top and the other two vertices on edges of the bottom of the slope), XY and Z accuracies of 0.056 and 0.100 m respectively were obtained.

The study [72] analysed the optimal number of GCPs for a flight at an altitude of 120 m and an area of 17.64 ha. The results show that increasing the number of GCPs improves the horizontal and vertical accuracy. The best accuracies were obtained for 15 and 20 GCPs (4.6 and 4.5 cm for RMSE XY and 5.8 and 4.7 cm for RMSE Z).

In the study [26], the accuracy results were presented as a function of GSD (here 6.8 cm). The flight was performed in a considerable area of 1225 ha. It was shown that increasing the number of GCPs has a positive effect on the final accuracy, reaching the error values per check points close to 3 × GSD in the amount of 50–60 and in the amount of 90–100 close to 2 × GSD. It was also found to be important to distribute the points evenly throughout the study area.

In the presented studies, classical block flights were analysed, while the publication [42] addresses the issue of the distribution and number of GCPs at corridor flight, where the dimension of one area significantly exceeds the other (2.1 km × 190 m). Four variants of GCPs distribution along the measurement object, which was a road, were analysed: 1) on both sides in a position of proximity, 2) on both sides in an alternate position, 3) on one side, 4) on both sides alternately and additionally at the ends of the road in a position of proximity. It was shown that in all cases the vertical accuracy is always lower than the horizontal accuracy, but both increase with increasing the number of GCPs (no less than 7 GCPs should be used to achieve RMSE XY ≤ 0.031 m and RMSE Z ≤ 0.081 m accuracies). The best accuracy results were recorded for variant 4, where RMSE XY of 0.029 m and 0.028 m and RMSE Z of 0.057 and 0.055 m were obtained using 9 and 11 GCPs respectively. Increasing the number of GCPs to 18, very similar RMSE values (XY 0.027 and Z 0.055 m) were obtained. The alternating and parallel distribution of GCPs was also compared in [76]. The results confirm that alternating distribution gives better results, especially for a smaller number of GCPs. The conclusion of the study is also that the GCPs should be placed at least every 100 m.

Accurate measurement of well-located GCPs can be time-consuming and expensive due to the need for additional fieldwork. In case of a large number of points visible in many photographs, the time of the indoor study is also increased due to the necessity of their precise identification and indication in the photographs. Moreover, when UAVs are used for remote sensing measurements, the necessity of GCP measurement invalidates the advantages of this method, namely its noncontact nature and speed [77]. Sometimes it is also impossible or difficult to perform a measurement due to complicated or inaccessible terrain such as glacial, river or mountain terrain or potential hazards [29, 78, 79]. These factors influenced the development of the direct georeferencing technique based on the measurement of the camera's EOP, allowing to reduce or eliminate the need to use GCPs [30, 80–82]. This allows the processing to be carried out automatically, for example using scripts, without the need for additional human intervention [83].

The UAV is constantly in motion during missions, so precise measurement of coordinates at the moment of shutter release for individual photographs requires the time synchronisation of both sensors. Direct acquisition of the values of EOP is performed by integrating on-board GNSS receivers for coordinates (x, y, z) and inertial measurement units IMU for orientation angles (ω, φ, κ). However, due to the size and weight limitations of UAVs, the use of these systems is not easy to implement [84, 85]. The very low accuracy of angular measurements makes their use in adjustment limited, so that georeferencing is mainly performed on the basis of the coordinates (x, y, z) of the centres of projection. Cheap GNSS navigation receivers installed on board the drones only allow for measurements to be made with metre accuracy (especially in case of vertical coordinate), so their use for direct georeferencing is not advisable [86]. The effective development of sensors and their miniaturisation allowed for the use of centimetre level accuracy (dual-frequency) phase receivers allowing the alignment of observations in different modes. Unfortunately, as the quality increases, so does the price of such solutions [87].

The acquired observations can be processed in several ways. The first method is RTK (real-time kinematic) in which corrections to observations are sent in real-time from a base station that is a receiver in the field (RTK) or a virtual base station for which corrections to the receiver are sent using the NTRIP protocol (NRTK). The studies [88] show that by using this method it is possible to achieve the centimetre mapping accuracies, while having a positive impact on both data acquisition time and the processing itself. However, both methods require the maintenance of a stable radio connection during the entire flight, and the NRTK method also requires access to the Internet. In the study [86] it was shown that using the RTK method for direct georeferencing allows similar results for RMSE XY (2–3 cm) as when using indirect georeferencing solutions incorporating GCPs in the alignment. The result for the RMSE Z value is three times larger than for the solution with GCPs, but it does not exceed 10 cm. Similar results for RMSE XY were shown in [47], and it was also found that the RMSE Z value varied from 2 to 10 cm depending on the flight.

If the maintenance of continuous communication between the base station and the receiver is not possible or can be unstable (for example, due to occlusions caused by UAV movement or the environment), the use of the RTK method can lead to errors [89]. In this case, the observations can be aligned in post-processing mode using the post-processed kinematic (PPK) approach. Many aspects related to the use of this method were analysed in the study [30]. These included issues of repeatability, reproducibility and efficiency to determine the possibility of using PPK in direct georeferencing. Based on the accuracy results obtained at the RMSE 3 cm level, it was shown that the use of accurate positioning allows for the replacement of the traditional approach using GCPs. The significance of the parameters of the camera used on the final accuracy was also highlighted. The studies [87] cover the issue of comparison of four georeferencing methods (using GNSS navigation receiver, single-frequency phase receiver with PPK mode, dual-frequency phase receiver with

PPK mode, indirect georeferencing with GCPs) and assessment of costs of particular solutions (50, 600, 8500 and 500 euros respectively). The results show that the highest accuracies (RMSE 1–3 cm) can be obtained using the georeferencing method with GCPs, however it is also the most time-consuming method requiring significant extension of both field and indoor works. The second most accurate method (RMSE 2–4 cm) using a dual frequency phase receiver with PPK mode significantly increases equipment costs. The use of a navigational GNSS receiver resulted in a RMSE of about 1 m, while using a single-frequency phase receiver with PPK mode resulted in a RMSE of about 20 cm. Considering time and cost, it should be taken into account that the employment of less accurate methods can also be useful, depending on the purpose of the activities (for example, visual inspection of remote sensing products with GSD values greater than 2 m or registration of drone images with airborne lidar data or orthoimagery with GSD up to 25 cm). The use of the PPK method for georeferencing with a DJI Phantom 4 RTK was also examined in a publication [90]. The results show that in most cases the accuracies were no worse than 0.043 m in XY and 0.072 m in Z. This shows that the technique can be used to generate accurate photogrammetric products, replacing the need to use GCP. This is especially important when mapping areas with limited accessibility, such as mountainous areas. In the study [91], DEMs obtained with georeferencing using the PPK technique with reference to three different ground bases were subjected to comparative analysis. The results obtained differ depending on the base used related to the coordinates read at the check points. It follows that the use of different ground bases influences the final results obtained.

Precise point positioning (PPP) is a method for obtaining precise positioning data without the need for additional base stations. The use of such a solution allows for simplifying the logistics of fieldwork as well as reducing the cost of additional equipment. The technique uses information on precise satellite orbits, clock parameters and corrections of atmospheric effects [92]. By combining these data with dual-frequency phase measurements and GPS code measurements, it is possible to achieve an accuracy of several centimetres. However, the technique is computationally complex and requires longer office time than other positioning methods. The studies [29] show that by applying the PPP method, it is possible to achieve final CPs RMSE values of studies of the order of 1–3 cm for the XY coordinate and 9–10 cm for the Z coordinate. These results are comparable with the PPK method for plane coordinates and slightly worse for the vertical coordinate, where RMSEs of 1–3 cm were achieved in the PPK method. The positions of the projection centres determined in this work with accuracy and precision at the centimetre level for the XY coordinate and at the decimetre level for the Z coordinate significantly improve the results obtained in the paper [93], which may be due to the longer flight times (25 and 29 minutes compared to less than 5 minutes) allowing the more accurate estimation of the GPS ambiguity parameters.

A comparison of direct and indirect georeferencing is provided in Table 3.

Table 3. Comparison of direct and indirect georeferencing

Georeferencing method	Advantages	Disadvantages
Indirect (ground control points)	– Suitable for use with drones without the ability to measure projection centre coordinates. – Potentially the most accurate method, desirable for self-calibration. – It allows for independent and reliable accuracy assessment by using subset of targets as check points	– It requires additional measuring equipment, preferably GNSS phase receiver, additional human resources or external company. – It requires additional work, the more work the greater the size of the study area is. – It can require the use of artificial measurement targets. – Difficult or impossible to use in hazardous or inaccessible areas. – It requires more intimate work, related to the measurement of the ground control points on the images
Direct	– It allows to avoid a lot of fieldwork associated with measuring ground control points. – It provides the possibility to quickly visualise a block of photographs immediately after the flight is performed (it is not required to perform a very accurate measurement of the projection centre coordinates). – It allows users to avoid the intimate work involved in measuring ground control points in photographs. – It allows for faster orientation of a block of photographs with SfM (structure from motion) methods as it is possible to quickly generate a co-visibility of the photographs and select pairs of images to be matched (it is not required to perform a very accurate measurement of the projection centre coordinates). – Suitable for use in hazardous or inaccessible areas where measuring ground control points is not possible	– It requires the aircraft to be equipped with a high-end GNSS receiver and antenna at considerable cost. – Additional costs are expected for the purchase or transmission of measurements from base stations. – In some situations and for some photographs, this method can give projection centre coordinates of lower accuracy (e.g. turns, where the antenna is tilted and visibility of many satellites can be lost). – As a rule, this method gives lower accuracies than orientation using ground control points. – Independent accuracy assessment is problematic – lack of check points. – This method requires visibility of satellites so it can be impossible or difficult to implement under certain circumstances (measurements in very deep mountain valleys, measurements of viaducts or bridges)

4. Photograph Blocks, Flight Methods

Another important factor influencing the accuracy of the study is the plan of the conducted flight. The SfM technique used to process UAV data is based on the extraction and subsequent matching of common features in consecutive images. In this way, a network of tie points is generated with simultaneous estimation of EOP and optionally with the performance of self-calibration. For these reasons, the performance of a flight requires an adequate number of photographs with significant overlap (at least 60%, often more than 70%) [35, 94]. When planning a flight, it is also important to take care of the legibility of terrain details in the photographs and the resolution. Therefore, the altitude of flight performance (height above ground level – AGL) becomes an important factor. The use of small, low-resolution, non-metric cameras requires that the flight is conducted at a much lower altitude than in the case of traditional manned photogrammetry, which also affects the final number of photographs that are taken within the scope of a given study. Taking many photographs at a low altitude with a high forward and lateral overlap has a positive impact on the final accuracy of the studies, however, it significantly increases both the time required for the fieldwork, as well as the time of indoor studies. This type of images configuration, the most typical for photogrammetric measurements, is called block mode. The limited work cycle of the camera can also be problematic in the case of flights. Especially in case of fixed-wing drones moving at a significant speed, it is not possible to plan an infinitely large coverage at a low cruising altitude. Sometimes the use of a traditional photogrammetric block consisting of multiple overlapping strips of photographs is also not cost-effective due to the linear nature of the object under study (rivers, roads, seashore). In this case, missions are carried out in a linear or corridor manner, where one of the dimensions of the study area significantly exceeds the other. Sometimes flights are also performed in circular or cylindrical configurations [95, 96]. Areas with very varied elevation are also a special case. For such areas, performing a raid at a fixed height may result in insufficient overlap between successive images. A solution to this problem can be to perform several independent missions at different flight altitude, to perform the flight manually without using a predefined plan or to perform a flight plan based on terrain contour tracking (using DEM) [32].

The flight plan relies on selecting a route defined by waypoints (which requires taking into account the planned overlap between strips), determining the frequency of taking photographs (which affects the overlap between successive photographs in a row), determining the speed of flight (which can affect the quality of captured images, especially when using a rolling shutter camera) and the AGL altitude (which affects the final resolution). Many programs have been developed that allow easy and detailed planning of a UAV flight taking into account the aforementioned parameters. The flight itself, on the other hand, can be performed manually or fully automatically based on a previously developed plan [97, 98].

Different flight configuration options for archaeological applications for a traditional 101 m × 112 m rectangular block were analysed in the studies [99]. They were differentiated in terms of AGL height (30, 40, 50, 60, 70, 80 m), overlap between photographs (40/70%, 50/80%) and the use or absence of GCPs. It was shown that decreasing the flight height has a positive effect on the detail of the obtained products which was also confirmed in the study [100] and increases the accuracy of the RMSE readings. For comparison, the value of the RMSE error when using an altitude of 30 m was 3.8 cm at

80/50% coverage and 5.4 cm at 70/40% coverage, while when using an altitude of 80 m it was 9.5 cm at 80/50% coverage and 10.0 cm at 70/40% coverage. The duration of operations for the different variants was also analysed and showed an increase with decreasing flight altitude. This is very unfavourable in the case of archaeological research, where it is important to take care of the lowest possible variability of lighting. This factor makes studies on the optimisation of the timing of such missions extremely important. Similar conclusions were reached in another study [101]. DEMs generated from images acquired at five different flight heights (50, 100, 150, 200, 250 m AGL) were analysed. The georeferencing was performed using 18 GCPs while the accuracy assessment was based on 385 CPs. The results showed that as the altitude increases, the accuracy decreases reaching 3.2, 4.0, 7.1, 10.9 and 16.6 cm 3D RMSE for each altitude, respectively. The study [102] also analysed accuracies for different flight heights (140, 160, 180 and 200 m AGL). Results of 0.043, 0.049, 0.052 and 0.057 m were obtained respectively, showing as before that lower altitude translates into higher accuracies. At the same time, it was noted that low altitude increases precision while increasing altitude reduces flight and processing time while still maintaining the required accuracy.

Other conclusions were drawn in the study [49]. Three different flight heights (67, 91, 116 m AGL) were analysed for an area of 0.25 km^2. The overlap was 80/70%. The results showed that the best accuracy was obtained for the variant performed at 116 m (2.3 cm RMSE Z and 3.7 cm RMSE total). At the same time, this variant was the most optimal in terms of work time.

The need to optimise flight duration, in addition to the issue of illumination changes that can lead to excessive shading and uneven object colour, is also significantly affected by the problem of limited battery life. The small load capacity of the UAV requires the use of low capacity batteries. An optimal flight plan can therefore be defined as the one that uses the least amount of energy and/or follows the shortest possible route. An important influence on increasing power consumption is the atmospheric conditions, in particular the wind, which the UAV must resist in order to maintain its planned flight path and speed. Therefore, the issues related to the optimisation of power consumption were analysed in the studies [25], using the example of a flight plan for the measurement of an opencast slope. A power consumption model was created on the basis of the battery performance study when flying in different directions and varying wind speed. On the basis of the developed algorithm, an optimal flight trajectory was created for which a 50% reduction in battery consumption and flight time was demonstrated in comparison to the traditional way of conducting flights. The work also included the development of an application that enables flight planning at steep slopes on the basis of the imported 3D model. This enables continuous tracking of the terrain to maintain a uniform height above the ground, translating into increased final resolution of the products. Thus, by using a cheaper UAV with a lower sensor resolution, products comparable to those obtained with more expensive equipment can be obtained. A similar manner of data acquisition but with a breakdown into flight lines with a specific altitude, was used in the studies [103].

A completely new approach to flight design was proposed in studies [95], taking into account the problems arising from complex geometries of measured objects. The functions of using traditional block and corridor flight modes were implemented. As a novelty in the block mode, the possibility of using DEM to determine flight parameters consistent with the real terrain surface was included. For the corridor mode, the ability to specify the object lines for measurement in addition to the flight path was added, allowing distance as well as inclination to be defined. In addition to improved versions of typical flight modes, a combined flight mode, combining block and line modes, particularly relevant for steep terrain was added. The combined mode includes automatic determination of the image acquisition position by defining the perpendicular flight direction, the line of objects to be measured and the inclination. In addition, a polygon extrusion mode is also included for measuring buildings based on a defined base and object height. In the tests carried out, the correctness of the proposed techniques was demonstrated.

5. Photogrammetric Software

A prerequisite for accurate photogrammetric products, in addition to properly and accurately performed field measurements, is also the proper performance of the indoor study. For this purpose, for data acquired with UAVs, the programs enabling the generation of dense point clouds, mesh models, digital terrain models and orthophotmaps [104, 105] are used. They are based on SfM (structure from motion) and MVS (multiple view stereo-vision) algorithms. They allow automatic extraction of common features in images that can be acquired at different scales, angles or orientations. The determined points are then treated as binding in the bundle adjustment process. The algorithm does not require information about the location of cameras or GCPs. It also allows camera calibration parameters to be determined automatically by treating them as unknowns in the alignment. The use of SfM-based software has therefore enabled the reduction of time and labour costs compared to traditional photogrammetric methods which require additional input data and much more operator intervention [94, 106].

A comparison of five commonly used UAV data processing programs (Agisoft PhotoScan, Inpho UAS Master, Pix4D, Bentley ContextCapture, MicMac) was conducted in another study [105]. Three different configurations of the number of GCPs used for the alignment were analysed. Configuration 1 involved the use of all measured points (18) as GCPs, configuration 2 involved the use of 11 points as GCPs and 7 points as CPs, while configuration 3 involved the use of 6 points as GCPs and 12 points as CPs. The need to concur on the input parameters of the alignment was highlighted in the paper because they have a large impact on the final results. In terms of configuration flexibility, the PhotoScan and the free MicMac were the best performers, with the other programs operating more like black boxes. For all of the programmes tested, the RMSE values of the Z coordinate were significantly higher than those of the XY coordinate. The results for Agisoft PhotoScan, Inpho UAS Master, Pix4D and MicMac were comparable, with less than 1 GSD for XY and less than 1.5 GSD for Z. The exception was Bentley ContextCapture which had significantly larger errors in the vertical coordinate.

The commercial software Agisoft PhotoScan with the free MicMac was compared in the study [107]. The accuracy of the DSM, generated from photographs acquired in suboptimal measurement conditions (complex, uneven terrain), was analysed. Final accuracies were determined from results for reference check points and by comparison with the TLS point cloud. It was shown that both programs allow to obtain satisfactory results. The same programs were compared in [57]. The conclusion of the research is that PhotoScan is less effective than the open-source Micmac due to its fixed workflow and few self-calibration model options. Micmac offers the possibility to include a more complex calibration model to reduce deformation in the DSM.

In research [108] three photogrammetric software were compared (Agisoft PhotoScan, Pix4Dmapper and Inpho UASMaster). Accuracy assessment was performed on check points and the results show that with use of 22 and 12 CGP all software deliver a 3D RMSE below the value of GSD. However, the lowest RMSE values were obtained with Pix4D. Agisoft and Pix4D were also compared in [48]. The results show that the 3D RMSE values were lower in Agisoft reaching 0.038 m, respectively, compared to 0.060 m in Pix4D for a configuration consisting of 7 GCPs.

Two commercial software Pix4Dmapper and 3DM Analyst were compared in [109]. The results show that both software gives similar results in DTM. However, Pix4Dmapper needs less time for processing while 3DM Analyst allows the process to be controlled after each step, a factor which can improve alignment accuracy.

Four different pieces of photogrammetric software (Agisoft Metashape, SimActive Correlator 3D, Pix4D Mapper, Web Open Drone Map) were compared in the study [110]. Processing time and output photogrammetric products were analysed. It was shown that in terms of running time Agisoft and Correlator 3D outperformed the other two programs. All of the software packages introduced visual artefacts in the output products, so for projects involving the evaluation of multi-temporal differences, it is best to consistently use one software program for greater certainty.

A different approach was presented in another study [111]. The authors showed that it is possible to prepare software to process UAV data into photogrammetric products using open-source Python libraries.

6. Conclusion

The review of studies conducted has shown that the issue of optimizing the acquisition and processing of photogrammetric data from UAV is a very important issue. Significant limitations in the use of UAV, such as battery life and low load capacity, influence the need to search for solutions enabling the cost-effective use of this method. A significant number of papers address the issues of reducing the time and cost of work while maintaining the highest possible accuracy. However, it is impossible to find the best solution as many factors influence the whole development process and the final product. Apart from accuracy issues, the most important of these are economic factors which can include the cost of equipment, cost and time of field and indoor work and other factors related to computational processes.

Special attention should be paid to the possibility of obtaining similar final results using different study variants. They can be differentiated in terms of the type of UAV used (fixed-wing, multi-rotor), type of camera shutter (rolling shutter, global shutter), method of camera calibration (pre-calibration, self-calibration), method of georeferencing (direct, indirect), method of obtaining the EOP (RTK, PPK, PPP), flight configuration (value of overlap, altitude, type of configuration: block, linear, combined, including oblique photographs) and the photogrammetric software applied.

Multi-rotor UAVs are usually less expensive than fixed-wing UAVs. They allow to take photographs in a motionless manner which has a positive effect on the quality or reduction of distortions caused by rolling shutters. Their use will be beneficial in the case of studies requiring greater accuracy but in small areas. For large area projects, a much better solution is to use fixed-wing drones that allow the acquisition of data from a much larger area and at the same time.

More expensive global shutters minimise the occurrence of geometric distortion in images. They should be used in projects requiring acquisition of large amounts of data in a short period of time by increasing the cruising speed. However, due to their much lower price, the rolling shutters are much more commonly used in UAV systems generating additional geometric errors associated with UAV movement, increasing with speed. On the other hand, the introduction of additional algorithms to model the distortions they generate allowed us to minimise the impact of such errors on the final accuracy of the studies.

In traditional photogrammetric techniques, an important stage of the work was the proper calibration of the camera, allowing the aligned elements of interior orientation to be obtained. The use of non-metric consumer grade cameras in UAV systems made it impossible to maintain stable parameters obtained in calibration results. The performance of pre-calibration allows to increase the accuracy of the study, however, it requires carrying out long-term additional measurements before or during the project. For this reason, the self-calibration method is used much more frequently in studies using UAV. In case of self-calibration, the condition for obtaining similar accuracy as in case of pre-calibration is to have a geometrically well-conditioned photograph network and accurate field measurements of ground control points. On the other hand, if the measurement of a large number of well distributed field points is not possible, a pre-calibration is a better solution.

One of the most essential stages of alignment is georeferencing. It can be performed indirectly using GCPs or directly on the basis of values of elements of exterior orientation measured in flight. Measurement of GCPs can be very time-consuming, especially when trying to obtain high coordinate accuracies over a large area. This results in a significant increase in work time. The miniaturisation of equipment allows the use of accurate GNSS receivers enabling the measurement of EOP in flight. Unfortunately, due to the high costs of such solutions, only low-accuracy navigation receivers are still installed in most UAV.

The direct georeferencing method, due to the continuous movement of the UAV during data acquisition, can be inaccurate or completely unfeasible due to the broken connection between the transmitter and the receiver. In order to increase the accuracy of the determined coordinates, various modes of alignment of the acquired observations are used. The most popular is the RTK mode that allows for permanent transmission of corrections from the base station to the receiver in a moving drone. However, due to the need for a permanent connection, this method can be very unreliable. Therefore, in cases where the project requires work over a larger area exposed to unstable connections, it can be better to use the PPK mode. This allows the alignment of observations after the flight without the need for constant communication. Unfortunately, due to the need for additional base stations, this method is expensive. A method that does not require additional equipment is PPP. It uses accurate information about the satellite's orbits and clocks. However, this mode is still the least used for aligning UAV position coordinates.

An important feature of UAV systems is the acquisition of data from a much lower attitude than in case of traditional aerial photogrammetry. For the same areas it is necessary to take much more photographs which makes the method profitable mainly for small areas. At the same time, obtaining images with a high overlap from lower altitudes has a positive effect on the final accuracy. It is therefore important to properly optimise the flight path and altitude to ensure the lowest possible battery consumption and thus increase the possible area to be covered.

Commercial software as well as freeware can be used to process data acquired via UAV. For both, similar final accuracies can be achieved. An important aspect to consider when choosing a particular software is the configurability of the initial parameters.

The study review shown that accurate final results can be obtained by using different methods of data acquisition or processing. The choice of variants depends on both the project requirements and economic factors. Any lack of accuracy of specific parameters can be compensated for by other factors. It is therefore possible to reduce the time and cost of work while maintaining high final accuracies.

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