UAV/UAS Photogrammetry for Use in Cadastral Surveying

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Keywords: Accuracy, Bundle Block Adjustment, Ground Control Points, Photogrammetry, Reference Data, RTK-GNSS, UAV/UAS.

Abstract

The potential of unmanned aerial vehicle (UAV) or unmanned aerial systems (UAS) photogrammetry for use in cadastral surveying tasks was explored as part of a research collaboration with the HafenCity University Hamburg and the Schleswig-Holstein State Office for Surveying and Geoinformation in Elmshorn, Germany. The building ensemble of a farm in Tensbüttel-Röst near Albersdorf, Germany was recorded with the DJI Phantom 4 Pro KlauPPK UAV system in various aerial flight configurations. The objective was to investigate and analyse the achievable geometric accuracy for a photogrammetric cadastral survey. The accuracy of the aerial triangulation was evaluated through the utilisation of diverse ground control point and check point configurations with the Agisoft Metashape software. The coordinates of the building were determined through the three different point measurement techniques. The roofscapes of the buildings and the 3D buildings were modelled as additional products. A digital orthophoto was also generated with the corresponding ground resolution. The accuracy, completeness and cost-effectiveness of the results of the UAV/UAS photogrammetry are discussed in comparison to the classical tachymetric building survey. It could be demonstrated that photogrammetric cadastral surveying is technically and economically feasible for building ensembles. However, the legal framework for this is not yet in place in some German federal states.

1. Introduction

In recent years, unmanned aerial vehicles/systems (UAV/UAS) have become a ubiquitous tool in geodetic practice. The significance of this technology in the contemporary era is evident from the consistently expanding UAV market and the rising number of users. There are currently over 400,000 UAV systems in use in the Federal Republic of Germany. Of these, 15% are used in the commercial sector and around 80% are used for surveying purposes (Kleisny, 2023). The growing prevalence of UAVs, including within the geodetic domain, can be attributed to the numerous benefits offered by their flexible utilisation and the rapid advancement of UAV technology. Nevertheless, despite the acknowledged benefits of this surveying approach in numerous geodetic contexts, there remain reservations among German surveying and cadastral authorities due to the narrow scope of prescribed guidelines, exemplified by those for measuring buildings. A significant number of federal states have thus far limited themselves to tachymetry and GNSS solutions in conjunction with SAPOS. In order for UAVs to be used more widely in cadastral surveying, it would be necessary to make modifications to the relevant legal regulations and instructions. In addition, it would be useful to investigate the potential of UAV photogrammetry for cadastral building surveying in practical tests and to compare it with classical building surveying using tachymetry.

In order to investigate the geometric accuracy of UAV photogrammetry for cadastral surveying, an ensemble of buildings on a farm in Tensbüttel-Röst near Albersdorf, Germany, was photogrammetrically surveyed using the UAV system DJI Phantom 4 Pro KlauPPK in three flight configurations (nadir, cross and oblique). The exterior orientation of the photos was determined using the GNSS measurements in post-processing with the KlauPPK software, while the geometric quality of the aerial triangulation was analysed using different ground control point and check point configurations in the Agisoft Metashape software. The coordinates of the building corners were measured in three ways - directly in the 3D point cloud, in stereo images and as a straight line section or as a section of two alignment planes. The dense point cloud was then used to generate the following additional products: building roofs, 3D buildings at various levels of detail, a digital surface model and a digital orthophoto at the appropriate ground resolution. Finally, the accuracy, completeness and costeffectiveness of the UAV photogrammetry results are discussed in comparison to the classical tachymetric building survey. This project was a collaboration between HafenCity University Hamburg and the Schleswig-Holstein State Office for Surveying and Geoinformation in Elmshorn, Germany.

After a literature review in Chapter 2 on existing studies on UAV photogrammetry in cadastral surveying in Germany and other European countries, the test area, the farm ensemble in the district of Dithmarschen (Schleswig-Holstein, Germany), is presented in Chapter 3. Chapter 4 describes in detail how the objects were surveyed using both conventional tachymetry and UAV photogrammetry, while Chapter 5 describes the data processing and the results obtained, which are finally analysed and compared in Chapter 6. Chapter 7 concludes with recommendations for the use of UAVs in cadastral surveying.

2. Related work

In practice, a number of German authors have already addressed the utilisation of UAVs in the real estate cadastre and in official cadastral surveying (Dankmeyer et al., 2019; Rembold, 2020; Schlösser and Kuhnt, 2020; Unger, 2023). Ten years ago, Rose (2014) reported on the practical experiences with the use of UAVs for the survey of real estate. This demonstrates that a discussion about the use of UAV/UAS photogrammetry in cadastral surveying in Germany is already underway. The issue has also been present for several years in other European countries. Manyoky et al. (2011) demonstrated the successful

https://doi.org/10.5194/isprs-archives-XLVIII-M-6-2025-169-2025

utilisation of unmanned aerial vehicle (UAV) photogrammetry in Swiss cadastral surveying at an early stage of development. In Poland, Kurczyński et al. (2016) reported on the potential use of UAS images in cadastral operations. Similarly, in Romania, Casian et al. (2019) demonstrated the feasibility of employing UAV photogrammetry in the production of topo-cadastral documentation. Moreover, Šafář et al. (2021) evaluated the utilisation of UAVs in the cadastral mapping of the Czech Republic. The evaluated UAV measurement methods, including image matching, intersection photogrammetry, and laser scanning, demonstrated the capacity to meet the accuracy requirements for point measurements in the Czech Cadastre.

Figure 1. Farm map with building functions (top) and orthogonal view of the coloured point cloud of the survey area (bottom)

3. UAV/UAS Test Area for Building Survey

The farm in Tensbüttel-Röst near Albersdorf in the district of Dithmarschen (Schleswig-Holstein, Germany) was selected as a test area for the building survey (Figure 1). The farmstead consists of a complex of buildings, including a residential structure and several stables and outbuildings. The barns are of a variety of designs, including open and closed structures, brick construction and a steel-framed barn. The pilot project is adaptable to different building types and construction methods. The farmstead covers approximately two hectares. As the farm is outside of UAV operating restrictions and the owners of neighbouring properties have been identified, obtaining consent for UAV flights and aerial photos was a straightforward process.

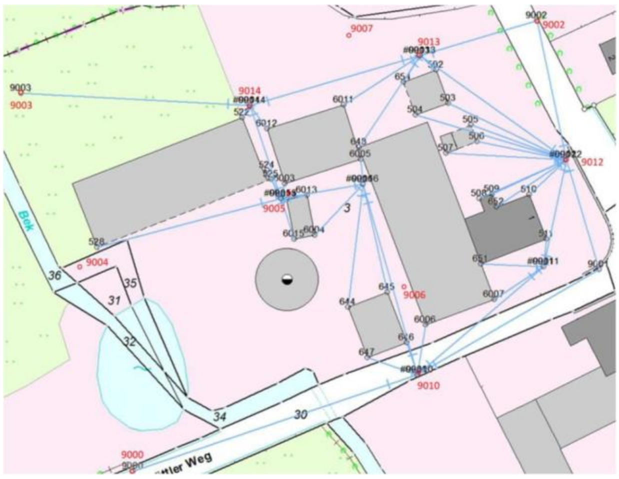

Figure 2. Site plan of the farm building ensemble including the tachymetric reference measurements (blue lines).

4. Data Acquisition

4.1 Official building surveying

The official building survey was carried out on 15 November 2022 using instruments from the Schleswig-Holstein State Office for Surveying and Geoinformation in Elmshorn, which are subject to a biannual quality check for use in cadastral surveying. The total station used is a Leica Viva TS16, which has a maximum angular measurement accuracy of 0.3 mgon and a distance measurement accuracy of 2 mm + 2 ppm for any surface (Leica Geosystems, 2024a). This was used in conjunction with a Leica GS16 GNSS receiver, which is a multi-frequency receiver (GPS, Glonass, Galileo and Beidou) with a positioning accuracy of 8 mm +1 ppm horizontally and 15 mm +1 ppm vertically for real-time kinematic measurements (Leica Geosystems, 2024b).

Four GNSS points (9000, 9001, 9002 and 9003, see Figure 2) were established and measured in the vicinity of the measurement area during the field survey. These points were measured using the SAPOS-HEPS correction service. Each point was measured twice at different times with an observation time of 30 seconds each. These points were then used as reference points in the 2D adjustment carried out in the 3A editor. The tachymeter measurements were linked to these four reference points by free stationing. The building points were then measured from seven stations (Figure 2).

4.2 Aerial UAV/UAS flights

The aerial survey was conducted using three separate UAV image flights on November 22nd, 2022. The photos were taken using a Zenmuse X4S camera with a focal length of 8.8 mm and a resolution of 20 megapixels on the UAV system DJI Phantom 4 Pro V2.0 (Figure 3). The UAV was operated via an Apple iPad utilising the DJI GroundStation Pro software. The image flight plan was created on site using the aforementioned software and the pre-established parameters. The unmanned aerial vehicle (UAV) is equipped with a KLAU PPK module, which was developed by Klau Geomatics in Nowra, Australia. The flights were conducted at varying altitudes, with each flight (east-west and north-south) having a longitudinal and lateral coverage (L/Q) of 80%/60%. Additionally, a third flight was carried out to obtain oblique images. The camera locations (black dots) and the image overlap is illustrated in Figure 4. The technical specifications of the aerial flights are summarised in Table 1.

Figure 3. UAV system DJI Phantom 4 Pro V2.0 and Apple iPad utilising the DJI GroundStation Pro software.

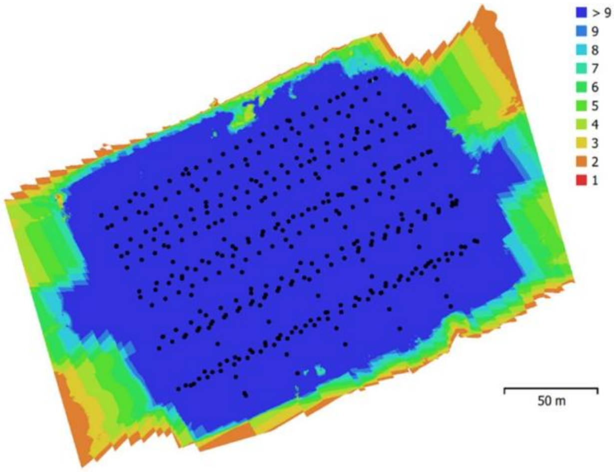

Figure 4. Camera locations (black dots) and image overlap.

Parameter	Longitudinal flight 1	Cross flight 2	Oblique flight 3
Altitude	40 m	50 m	45 m
View angle	nadir	nadir	oblique (30°)
GSD (nadir)	10.9 mm	13.7 mm	12.3 mm
Overlap L/Q	80%/60%	80%/60%	80%/60%
Flight time	13 min	3 min	3.5 min
# photos	219	68	83

Table 1. Technical specifications of the three aerial UAV flights.

In the process of planning an image flight, the flight altitude is specified, which, in conjunction with the fixed focal length of 8.8 mm, gives rise to the photo scale. This is multiplied by the pixel size in the image (in this case 2.4 µm) to obtain the pixel size on the ground (GSD = Ground Sampling Distance), which corresponds approximately to the point measurement precision in object space. In order to calculate a dense point cloud, an overlap of at least 80%/60% is typically required. To ensure the camera constant is calibrated with reliability and significance, it is recommended that two different flight altitudes be used in flight directions rotated by 90 degrees (cross flight). A further flight with oblique shots enables more precise camera calibration and a superior view of the area beneath the roof overhangs due to the differing perspectives. Consequently, the corners of the building can be depicted and analysed with greater reliability in the image or point cloud. For further technical information on aerial flight configurations and aspects of quality control for UAV applications in photogrammetry, please refer to Przybilla and Kersten (2022).

Figure 5. Distribution of ground control points and b/w target.

During the total station survey, the coordinates of ten ground control points (GCP) were determined through the utilisation of GNSS measurements, which were subsequently signalised with black and white target markers prior to the UAV flights (Figure 5).

5. Data Processing and Results

4.1 Evaluation of the Tachymeter Measurements

The total station data were subjected to analysis using the 3A Editor, a software program developed by Verti-GIS. This editor forms part of the 3A product line and is based on the ArcGIS platform from ESRI. It serves as a collection, processing and qualification component for the AFIS-ALKIS-ATKIS data. In the 3A editor, the measurement data is adjusted with the four GNSS points serving as datum points. The 2D adjustment resulted in standard deviations of 6 mm for the 2D points. The buildings and components were transferred to the ALKIS inventory using these building points. In cases where building points were not measured, they were determined mathematically by calculating the lengths of the building sides in the field.

4.2 Evaluation of the UAV image flights

The image orientations and point clouds were calculated using the Agisoft Metashape Professional 1.8.4 software. The GNSS observations recorded during the flight were previously processed using KlauPPK software in order to determine the camera positions. It is possible to calculate the desired positions using RINEX data from a base station in post-processing (PPK) in lieu of utilising an RTK (Real-Time Kinematic) solution. For this purpose, either a dedicated GNSS receiver positioned at a known point within the object area or data from a nearby SAPOS station can be employed. The calculated camera positions were determined using KlauPPK software and transformed into the desired reference system (ETRS89/UTM32 and DHHN2016). The positional accuracy ranges from 3 cm (fix) to 25 cm (float) as illustrated in Figure 6. The coordinates of the projection centres were employed in the bundle block adjustment, with consideration given to the standard deviations and corresponding weightings. It is possible to orient images with a sufficient number of ground control points without an RTK or PPK solution. However, the desired accuracy can be more readily achieved with the use of such a solution, as fewer control points are then required, thus saving time in the field and in the office.

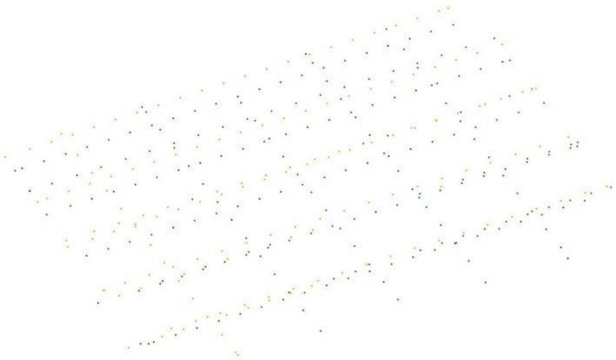

Figure 6. Calculated camera positions using KlauPPK software, the positional accuracy ranges from 3 cm (fix, green) to 25 cm (float, yellow).

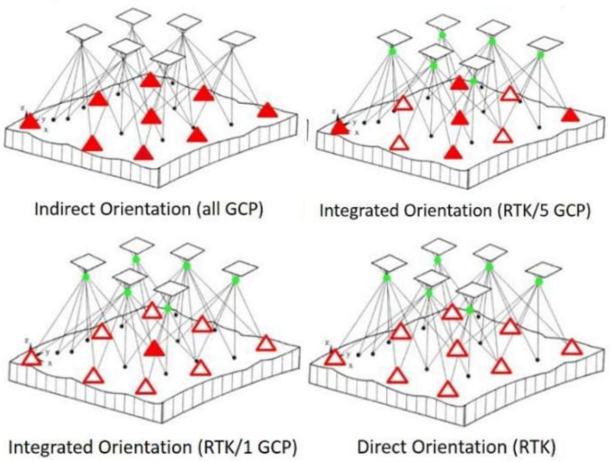

Figure 7. Used options for the determination of the orientation in the bundle block adjustment (after Przybilla and Kersten, 2022): V1 with all GCP, V2 with RTK and 5 GCP, V3 with RTK and 1 GCP, and V4 with only RTK solution.

The bundle block adjustment was computed with four different variants as depicted in Figure 7: V1 with all 10 GCP, V2 with RTK and 5 GCP, V3 with RTK and 1 GCP, and V4 with only RTK solution. The results of the bundle block adjustments are presented in Figure 8. The XYZ residuals of the GCP are within the range of 1 cm. However, the bearing only on the RTK exterior orientation shows a notable discrepancy in the height coordinate at the check points (see V4). Therefore, the utilisation of at least one GCP is essential for the bundle block adjustment using precise camera locations through RTK/PPK-GNSS, although the Z coordinate is not so important for the further processing in 2D cadastre surveying.

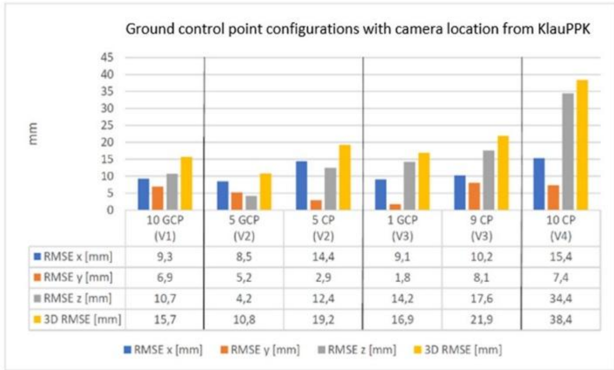

Figure 8. Results of bundle block adjustment for ground control points (GCP) and check points (CP).

A dense, coloured 3D point cloud comprising 110 million points was created for the purpose of measuring the building points. Three distinct methodologies were employed. Method 1 entailed direct measurement within the dense point cloud. Method 2 involved a spatial intersection in the orientated stereo images. Method 3 comprised a straight-line section or the section of two alignment planes. It was not possible to utilise measurements in the triangular mesh, as the corners of the buildings exhibited rounded characteristics (Figure 9, left), which were a consequence of noise in the point cloud (Figure 9, right). However, direct measurements in the point cloud (method 1) delivered the best result. A total of 32 building points, determined using a total station, served as a reference. Of the photogrammetrically measured corners, 87.5% were found to be within the permissible deviation of 5 cm. The average linear deviation was 1.4 cm. The coordinates for each building point were determined by averaging three measurements in the point cloud. One side of the building was barely depicted due to the lack of oblique photos in the building edge area caused by a flight mission planning error (Figure 10, top right, and Figure 11, bottom), which caused problems for precise measurements in the point cloud.

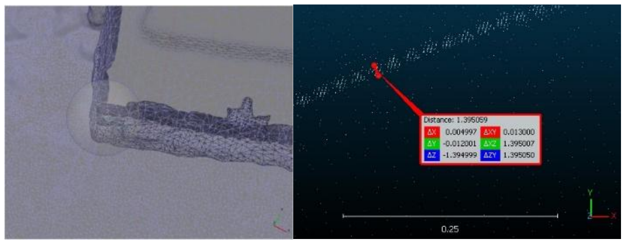

Figure 9. Point measurement in a triangular mesh (left) and noise of approx. 1-2 cm in the point cloud (right).

The straight-line method achieved 78% of the points within the error tolerance and therefore delivered a good result. However, the method is more complex than direct measurement in the point cloud and should therefore only be recommended as a supplement if this is really necessary. The method of spatial intersection did not lead to the desired result. The measurements in the stereo images could not be carried out satisfactorily and the deviations were outside the tolerance. However, Rembold (2020) shows that linear deviations of less than 3 cm can also be achieved with this method.

Figure 10. Missing point cloud on a façade (top left), top view (top right) and oblique view (bottom) of the point measurements of a building corner in the point cloud.

Figure 11. Perspective view of the point cloud of the farm building ensemble including points on the facades (top) and with missing points on the facades (bottom).

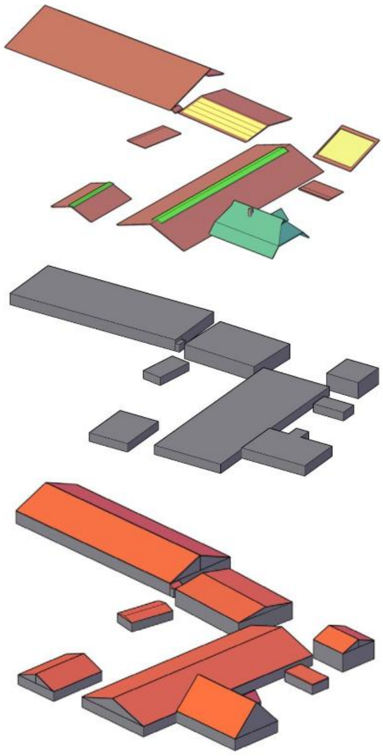

Figure 12. Constructed roof landscapes (top), 3D building models LoD1 (centre) and LoD2 (bottom).

In addition to the measurement of the buildings for the real estate cadastre, an investigation was conducted to ascertain the efficacy of modelling the buildings from the dense point cloud. The initial step involved the creation of roof landscapes (Figure 12, top). The coordinates of the corner points of the roofs were imported into AutoCAD, after which polylines and solids were constructed from the points. Subsequently, 3D building models were created that correspond to both LoD1 and LoD2 (Figure 12, centre and bottom). Finally, detailed 3D building models with windows, doors and other elements were constructed to test whether the resolution of the dense point cloud was sufficient for this purpose. The point cloud was imported into AutoCAD in RCP format and used directly for the 3D construction. Figure 13 shows the buildings of the farm as detailed 3D building models, which roughly correspond to LoD3 with this level of detail.

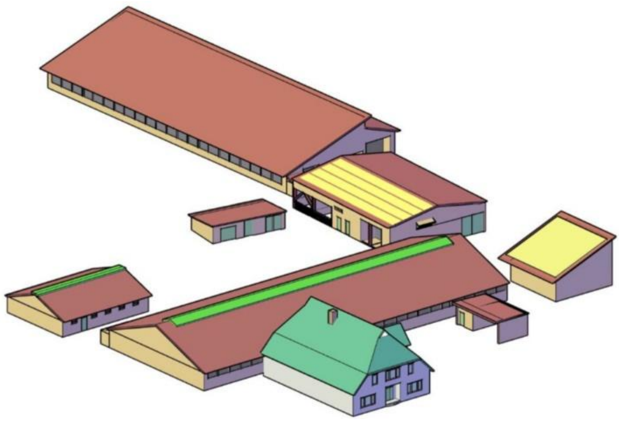

Figure 13. Detailed 3D building models of the farm constructed in the point cloud, which may comply with the LoD3 standard.

Figure 14. Digital Orthophoto with 1.1 cm GSD integrated in Google Map data.

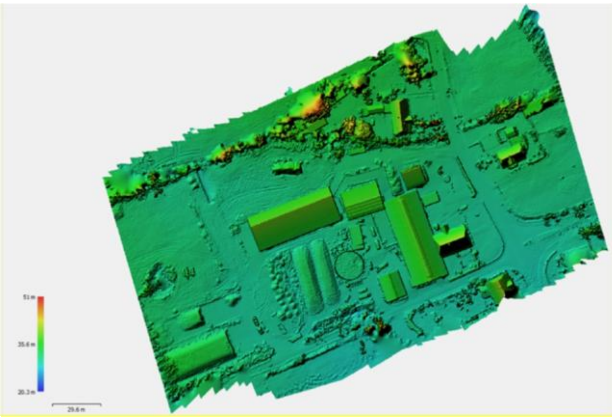

Figure 15. Digital Surface Model of the farm building ensemble. The application of UAV photogrammetry can facilitate the generation of geodata products with enhanced resolution and information content. This includes the production of digital surface models (Figure 14) and high-resolution digital orthophotos with 1.1 cm GSD (Figure 15), which can provide valuable findings for various applications.

6. Discussion and Comparison of the Two Methods

The accuracy, completeness and cost-effectiveness of the results of the UAV/UAS photogrammetry are discussed in comparison to the classic tachymetric building survey. Therefore, the two recording methods are subjected to a comparative analysis. The standard deviation for the 32 building points in the tachymetric survey was found to be 6 mm. The standard deviation for the building points in the point cloud resulting from the UAV photogrammetry measurements was 8.4 mm. The specified measurement tolerance was met for 28 of the 32 points (87.5%). The average deviation of the spatial vector was 14 mm (maximum 37 mm). The remaining points could not be clearly defined and were therefore difficult to measure. This was due to the lack of oblique images of the UAV image flight in the area of these points. It is possible that the result could be significantly improved by optimising the image flight planning.

A total of approximately eight hours was required for the tachymeter measurements, including the subsequent evaluation. The aforementioned hours were distributed equally between the field service and the office service. With regard to the UAV measurement, one hour was attributed to the GNSS control point measurements and photo flights on site, which were conducted by two individuals. Additionally, approximately 10 hours were allocated for the evaluation process, comprising the image orientation, camera calibration, the calculation of the dense point cloud, and the measurement of the building points.

A conventional building survey typically takes around eight hours to complete, while a UAV survey (flight and data processing) takes around twelve hours. However, it is important to note that the use of UAVs becomes increasingly advantageous when surveying multiple buildings or larger areas at the same time. Despite the need for more images, the automated processes involved in the subsequent evaluation and measurement in the point cloud reduce the manual effort required, while increasing the computing time.

In comparing the costs, it is essential to consider the financial implications of the equipment. The principal factor contributing to these discrepancies is the tachymeter, which in this instance (Leica TS16) is priced at estimated €30,000. In comparison, the DJI Phantom 4 Pro + PPK module is already available for approximately €5,000. The GNSS rover (Leica GS16) is priced at approximately €16,000. However, this instrument is necessary to determine the GCPs in both methods.

7. Recommendations for the Use of UAV Photogrammetry in Cadastral Surveying

The findings of this investigation have yielded recommendations for the utilisation of unmanned aerial vehicle (UAV) photogrammetry in cadastral building surveying. In the context of surveying a single building, the utilisation of this method is not economically viable in comparison to the traditional approach involving the use of a total station. Nevertheless, UAV photogrammetry is more efficient for the surveying of building ensembles or new development areas comprising numerous buildings. When planning aerial UAV flights, a GSD of 1 - 1.5 cm should not be exceeded in order to ensure the required accuracy (reliable deviation [d] < 5 cm with proof of identity for multiple determinations). It is recommended that the image flights be conducted with both cross flights at varying flight heights and additional oblique images to ensure optimal views of the building facades and corners. Furthermore, in addition to utilising GNSS RTK to ascertain the positions of the camera positions of the UAV system, it is imperative to employ at least one ground control point in the centre of the survey area. This is to ensure control and to circumvent any potential height offsets. It is recommended that signalised check points be used to assess the quality of the results of the bundle adjustment and camera calibration. Furthermore, the deviations at the check points can be used as proof of accuracy. It is advisable to employ personnel with photogrammetric expertise for the aerial flights and the evaluation of the UAV image data.

8. Conclusions and Outlook

This article presents a comparative analysis of a conventional building survey conducted using a total station with a building survey conducted using UAV image data. The results demonstrated that UAV photogrammetry is a viable method for cadastral surveying, as the requisite accuracy levels were attained. The necessity for a supplementary or alternative method to traditional total station surveying may be negated, or at the very least reduced, depending on the number of buildings to be surveyed and the extent of the area. The high information content of the generated image data allows for the production of additional products, including 3D building models, orthophotos, terrain models, and surface models. However, in many federal states, there are surveying regulations and instructions that are not yet designed for the use of UAVs. Furthermore, the legal requirements for UAV operation for an authority without security tasks are also problematic. Nevertheless, the use of UAVs in official surveying should be promoted in order to establish this measurement method among German surveying authorities and utilise its advantages. The authors think that there will be an increasing importance of UAV photogrammetry in cadastral surveying in the future.

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