Investigations on the geometric quality of commercially available cameras for UAV applications

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Key words: Unmanned aerial vehicle, UAV test field, camera sensors, geometric quality parameters, workflow

SUMMARY

The geodetic-photogrammetric test field at the industrial monument Zollern colliery in Dortmund offers a scenario for carrying out geometric and radiometric tests of UAV systems. The foundation for this builds a geodetic precision network (position and height accuracy approx. 2 mm) with a total of 45 ground control points, distributed over an area of approx. 7 hectares. Within the scope of a campaign carried out in autumn 2017, various UAV sensor systems were tested under comparable conditions. Within this paper geometric investigations of two current DJI cameras, Zenmuse X4S (20 Mpix) and X5S (20.8 Mpix), as well as a Phase One IXU 1000 (100 Mpix) are presented. While the Zenmuse cameras reflect the current state of development of the manufacturer DJI, the medium format camera system from Phase One is primarily settled in the classic aerial segment. However, the desire for increased measurement accuracy (e. g. for engineering applications) also makes such a high-performance sensor interesting for UAV applications.
In addition to the configuration of the test field, the system comparison requires identical parameters for flight planning, in particular image overlapping, a complete cross flight configuration at different flight altitudes and the definition of a uniform ground resolution (GSD=14 mm).
The investigations show clear differences in the achievable quality of the cameras. Though the high-priced Phase One system shows the best results, the most cost-effective system, the Zenmuse X4S, delivers only slightly worse results. In contrast, the Zenmuse X5S performs significantly worse than the other systems, mainly resulting from the mechanically unstable camera concept with interchangeable lenses. Finally, the comparison of the software products Pix4Dmapper and Agisoft PhotoScan shows significant differences in the results of image orientation.

ZUSAMMENFASSUNG

Das geodätisch-photogrammetrische Testfeld auf dem Areal des Industriedenkmals Zeche Zollern in Dortmund bietet ein ideales Szenario zur Durchführung geometrischer und radiometrischer Tests von UAV-Systemen. Die Basis hierzu bildet ein geodätisches Präzisionsnetz (Lage- und Höhengenauigkeit ca. 2 mm) mit insgesamt 45 Bodenpasspunkten, verteilt über eine Fläche von ca. 7 ha. Im Rahmen einer im Herbst 2017 durchgeführten Kampagne wurden verschiedene UAV-Sensorsysteme unter vergleichbaren Bedingungen

getestet. Dieser Beitrag stellt geometrische Untersuchungen zweier aktueller DJI-Kameras, Zenmuse X4S (20 Mpix) und X5S (20,8 Mpix), sowie einer Phase One IXU 1000 (100 Mpix) vor. Die Zenmuse Kameras geben den aktuellen Entwicklungsstand des Herstellers DJI wieder, während das Mittelformat-Kamerasystem von Phase One vorrangig im klassischen Luftbildsegment zu finden ist. Allerdings macht der Wunsch nach gesteigerten Messgenauigkeiten (z. B. für Ingenieuranwendungen) einen derartigen Hochleistungssensor auch für UAV-Applikationen interessant.

Voraussetzung für den Systemvergleich bilden, neben der Konfiguration des Testfeldes, identische Parameter für die Flugplanung, hier insbesondere Längs- und Querüberdeckung, die Durchführung einer vollständigen Kreuzbefliegung in unterschiedlichen Flughöhen sowie die Festlegung einer einheitlichen Bodenauflösung (GSD=14 mm).

Die Untersuchung ergibt deutliche Unterschiede in der erreichbaren Qualität der Kameras. Das hochpreisige Phase One System zeigt die besten Ergebnisse, allerdings liefert das preiswerteste System, die Zenmuse X4S, nur geringfügig schlechtere Resultate. Im Gegensatz dazu fällt die Zenmuse X5S deutlich ab, vorranging begründet in dem mechanisch wenig stabilen Kamerakonzept mit Wechselobjektiven. Der abschließende Vergleich der Software-Produkte Pix4Dmapper und Agisoft PhotoScan zeigt zum Teil signifikante Unterschiede in den Ergebnissen der Bildorientierung.

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1. INTRODUCTION

UAV-based image acquisition has become an established geodetic-photogrammetric data acquisition method, which is used in many application areas with various demands on the quality of the results – from decimeter to millimeter scale– and due to its great flexibility. In the context of a system procurement, users are usually interested in highly developed UAV platforms, often neglecting to inform themselves sufficiently about the quality of the integrated camera. The selection and quality/geometry of the camera is the most important factor with regard to the results to be achieved (e.g. 3D point clouds, orthophotos, etc.). The market for digital cameras, which are used in UAV-based scenarios, is subject to continuous change, with new cameras being launched very frequently, so that existing systems become quickly obsolete. UAV of the manufacturer DJI have a considerable market presence and are primarily used in film and video productions. In the meantime, however, they have also found widespread use in geodetic applications. The Zenmuse X4S (20 Mpix) and X5S (20.8 Mpix) DJI cameras reflect the current state of development of the manufacturer but come with very different designs (Table 1, Figure 1).

Tab. 1: Technical data of the camera systems under test

Manufacturer	Phase One / Coptersystems	DJI	
Camera	Phase One IXU1000	Zenmuse X5S	Zenmuse X4S (Phantom 4 Pro)
Lens	Rodenstock 50/5.6	DJI MFT ASPH 15/1.7	Integrated 8.8/2.8
Interchangeable Lens	Yes (mechanically stabilized)	Yes	No
Focus	Mechanical: ∞	Electronical: ∞	Electronical: ∞
Shutter	Central (mechanical)	Rolling	Central (mechanical)
Resolution [MPx]	100	20,8	20
Sensor Format [mm]	53.4×40.0	17.3×13.0	13.2×8.8
Number of Pixel	11.608×8708	5.280×3956	5.472×3648
Pixelsize [µm]	4,6	3,28	2,4
Focal Length [mm]	50	15	8,8
Field of View (FOV) / (diagonally)	67,4°	73,6°	83,8°
Price [€]	50 - 60.000(*)	2.200	800

(*) depending on the lens used

While the proprietary DJI cameras are used in conjunction with the Phantom 4 Pro and Inspire 2 series, the Phase One IXU 1000 (100 Mpix) is a medium format camera system that is typically used on classic aerial photography platforms. For the Zollern colliery tests, a powerful UAV from Coptersystem (Coptersystems 2018), with a maximum take-off weight of 10 kg, was used. The achievable flight time with this copter is approx. 20 minutes and thus comparable to that of a DJI flight platform (Figure 1). Recently DJI supports Phase One cameras in conjunction with the Matrice series.

Phase One IXU1000
(100 Mpix)

DJI Zenmuse X5S
(20,8 Mpix)

DJI Zenmuse X4S
(20 Mpix)

Coptersystems
Multicopter

DJI Inspire 2

DJI Phantom 4 Pro

Fig. 1: Cameras and carrier platforms under test

In manned aerial photogrammetry, the establishment and use of test fields has been a field-proven procedure for investigating the quality of photogrammetric camera systems over many decades. In this context, the Vaihingen/Enz test field of the University of Stuttgart (Cramer & Krauß 2008) displays a prominent example. Furthermore, test fields are also used for the in-situ calibration of digital aerial cameras (Mueller & Neumann 2016). However, these test fields do not meet the requirements for testing UAV systems. In addition to the size (adapted to the classical image flight), the accuracy of the reference points, which in the case of a UAV test field must be in the sub-centimeter range (chapter 2), is primarily lacking.
The aim of this study is to compare the geometric quality of the cameras involved. Additionally, the investigations focus on parameters that can influence the geometric quality of the image blocks.

2. THE UAV TEST FIELD ZOLLERN COLLIERY

The UAV test field at the industrial museum Zollern colliery in Dortmund (LWL 2018) was established by the Bochum University of Applied Sciences (HSBO) in 2014 and has been the foundation for various campaigns so far (Nex et al. 2015; Przybilla et al. 2015; Gerke & Przybilla 2016; Cramer et al. 2017; Przybilla et al. 2017). Further examples concerning experiences with UAV test field calibration are e. g. presented by Oniga et. al (2018).

The Zollern colliery was built in 1898-1904 on the western outskirts of Dortmund (ȯ51° 31′ 4″ N, 7° 20′ 5″ O) in the district of Bövinghausen in the art Nouveau style. After its closure at the end of the 1960s, the Regional Association Westphalia Lippe (LWL) integrated the colliery into the decentralized Westphalia industrial museum in 1981 (Wikipedia 2018). Today, the colliery is not only a museum with permanent and changing exhibitions, but also a place for local recreation as well as cultural and scientific events.

The UAV test field set up by the HSBO covers almost the entire area of the colliery. Its extension is 320 m × 220 m (approx. 7 ha). The highest vertical objects are given by two pitheads with about 40 m height. In general, the test field is based on 45 signalized ground control points arranged in a grid (Figure 2).

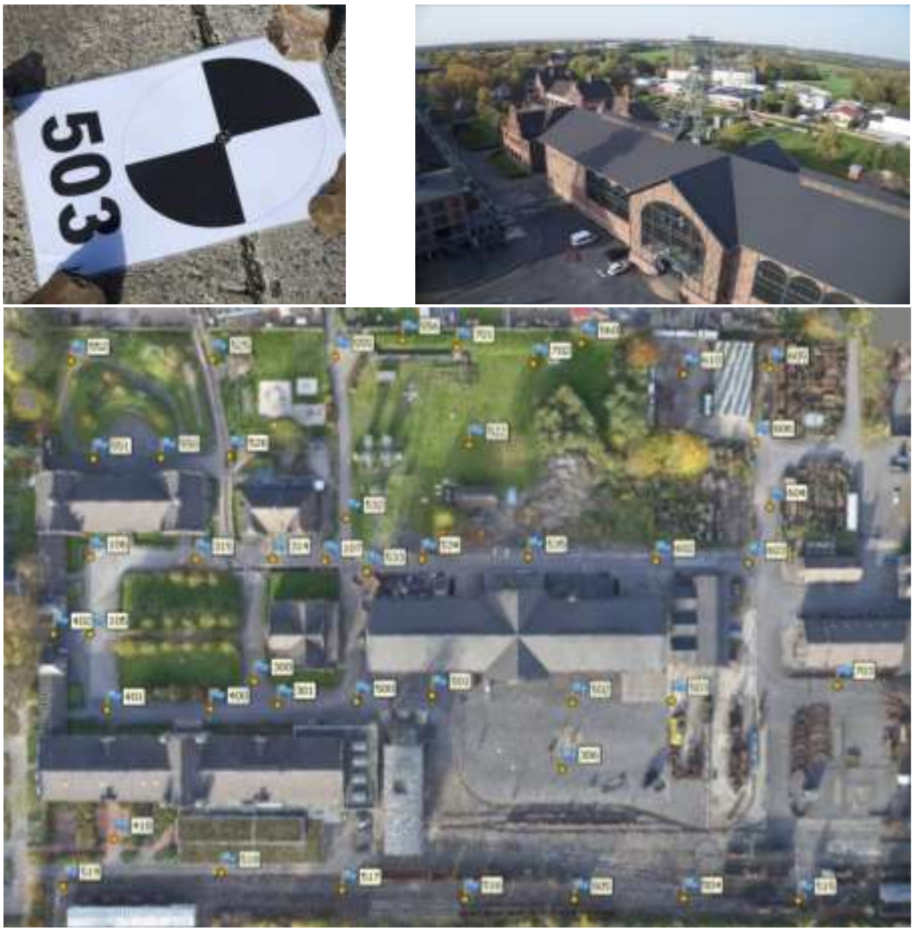


Fig. 2: UAV test field Zollern colliery. Top: Target for signalizing the GCPs and view of the area. Bottom: Point cloud with signalized GCPs (UAV flight from October 2017)

An overview of the implemented geodetic measurements for establishing the UAV test field is given in Figure 3, including the quality of the results (Przybilla et al. 2018).

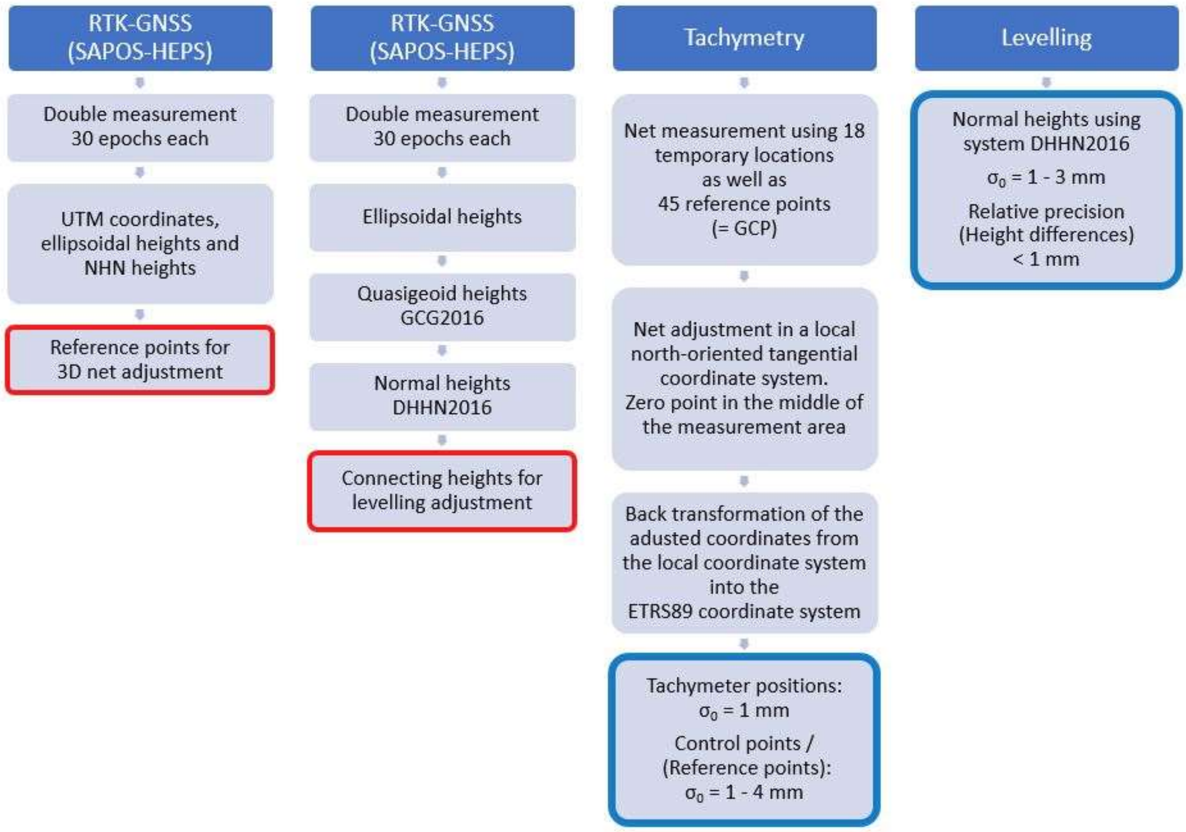


Fig. 3: Workflow of geodetic measurements and data processing (GCG2016 - German Combined QuasiGeoid, the height reference for the transition between geometric heights in ETRS89/DREF91 and physical heights in DHHN2016, the German height reference system).

3. DATA CAPTURING CONCEPT

In order to ensure comparability of the camera systems within the test, a uniform ground resolution (GSD) of 14 mm was defined in advance for all systems (flight configuration: Regular / R). Consequently, the platforms performed at different flight altitudes (Table 2). Additionally, this was supplemented by flights in a cross arrangement (Cross / C), whereby the flight altitude deviated from the normal arrangements by 20 % in each case (Figure 4). It should be noted, that the extension of the recording concept by the cross arrangement was used because of its positive effect on the in-situ calibration of the camera, as shown before (Przybilla et al. 2015; Gerke & Przybilla 2016).

Tab. 2: Systems, flight arrangement and altitude

	Phase One IXU1000	DJI Zenmuse X5S	DJI Zenmuse X4S
Regular (R)	120m	60m	50m
Cross (C)	148m	72m	60m

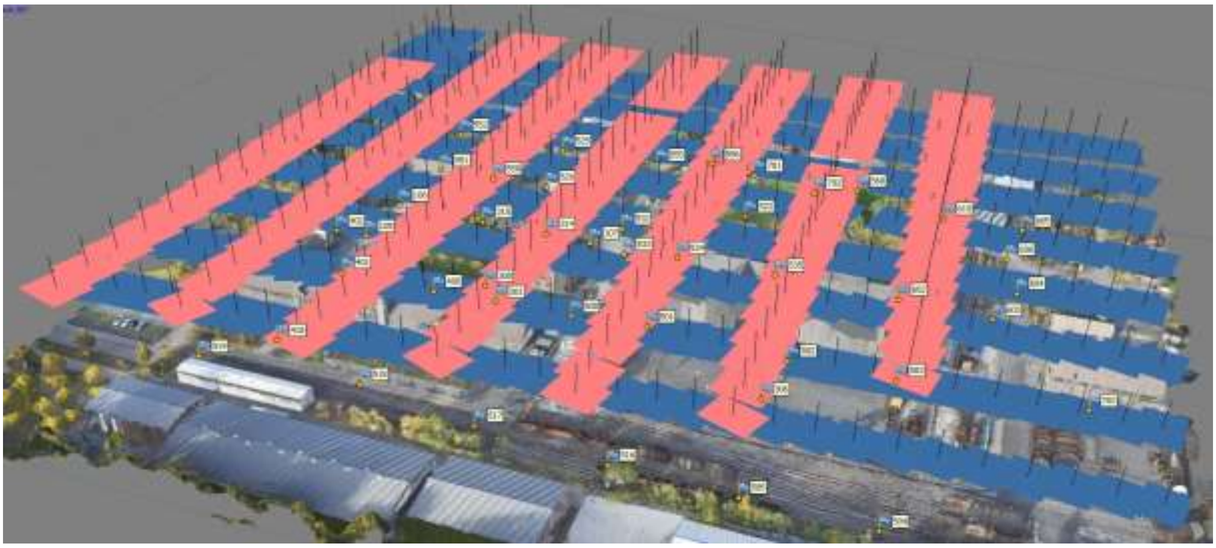


Fig. 4: Flight arrangement Regular (R) and Cross (C), (Image block with Zenmuse X4S)

4. RESULTS OF INVESTIGATION

One of the investigation's focus was the determination of parameters that influence the geometric quality of the image blocks (Figure 5). Therefore, the aim was to investigate the influence of those parameters.

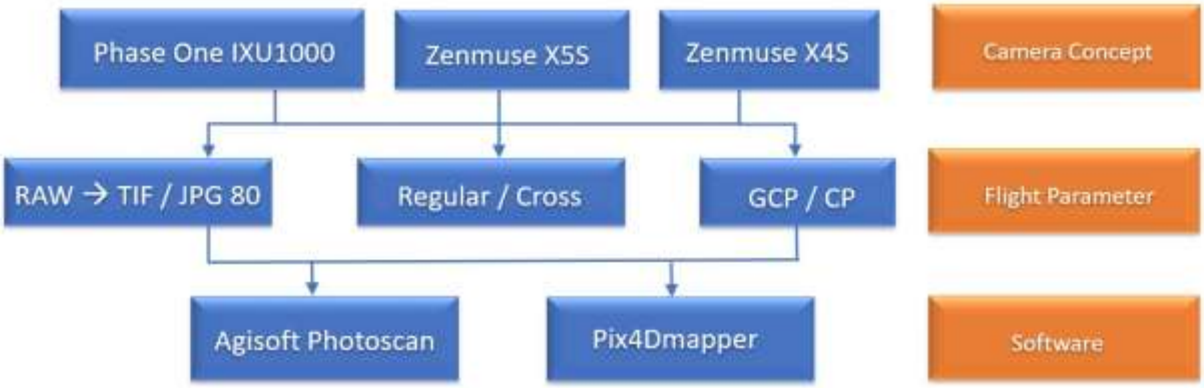


Fig. 5: Parameters influencing the geometric quality of the image blocks

To do so, the root mean square errors (RMSE values) at the ground control points (GCP) were evaluated. These statistical values are results of the bundle block adjustments (BBA) using the evaluation software Agisoft PhotoScan and Pix4Dmapper respectively. The calculation variants are depending on the following parameters:

- block configuration (number of control points and arrangement),
- number of cameras in the self-calibration process (interior orientation),
- flight arrangement (Regular – R / Cross – C),
- evaluation software used.

Importantly, the set of interior orientation parameters for each camera tested, was identical for all subsequent calculations with Agisoft PhotoScan (focal length: f; principle point: cx, cy;

radial symmetric distortion: k1 - k3; affinity and non-orthogonality: b1, b2; tangential asymmetric distortion: p1, p2).

4.1 Effects of ground control point configuration

The number and arrangement of the control points usually has a significant influence on the block geometry. Substantial effects of different ground control point configurations on the final products (e. g. DEM) have been shown by Lindstaedt & Kersten (2018) in several UAV-based surveys in Ethiopia. On the one hand, a high number of control points stabilizes the block, while on the other hand, it requires a considerable effort for terrestrial surveying on site. Since UAV systems actually provide differential GNSS (RTK) for block referencing only to a small extent (Grayson et al. 2018), the distribution of the control points is often based on schemes from the time of the "analogue" image flight (Figure 6). Deviating from the distribution shown here, in practice, all points are measured as 3D coordinates – often using GNSS.

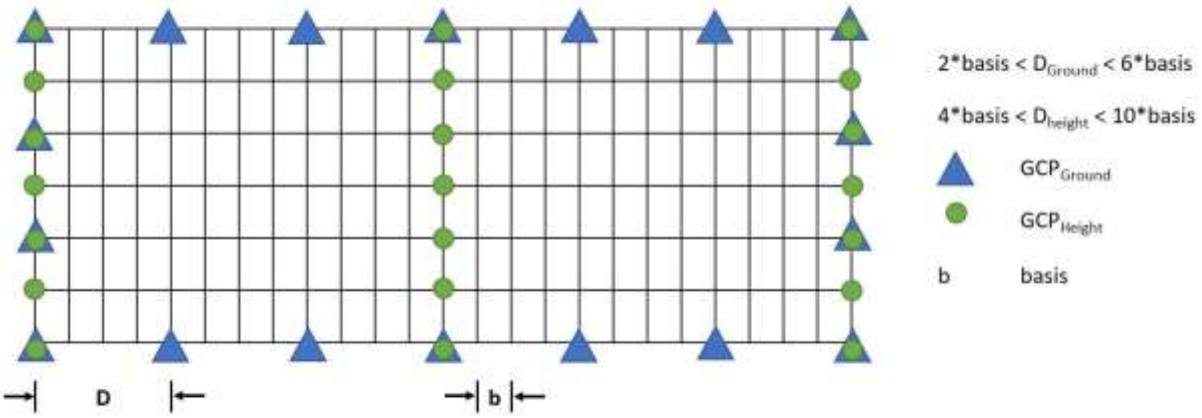
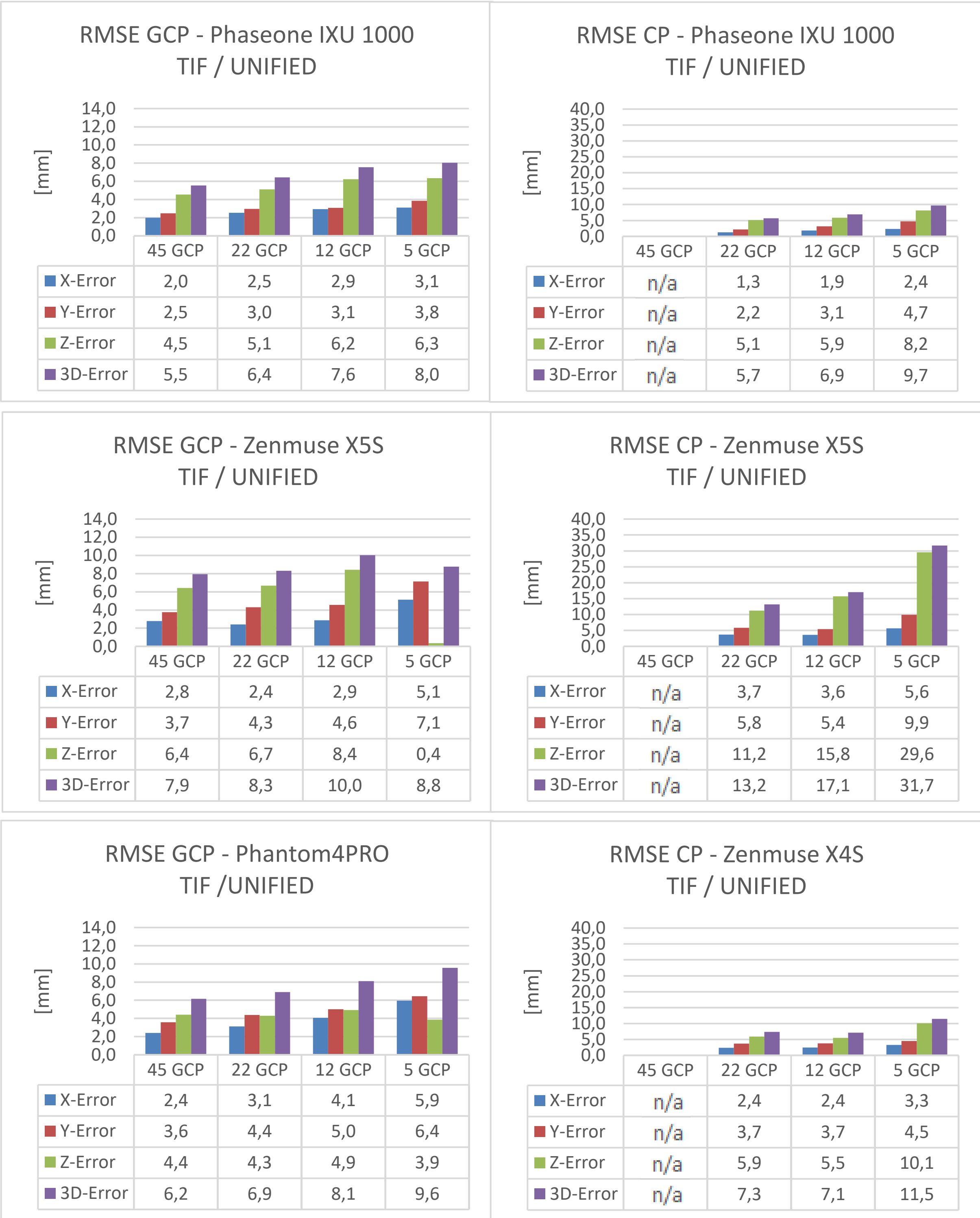


Fig. 6: Schematic arrangement of GCPs during (analogue) image flight (Kraus 1994)

Figures 7-9 show the effects of the varying ground control point distributions for the three cameras tested within this investigation. The results are based on a block reference with 45, 22, 12 and 5 GCP respectively. Essentially, those GCPs are distributed in a grid over the area (Figure 2). The reduction of the GCP leads in turn to an increase of the number of control points (CP), from 0 to 23, 33 up to 40 CP, thus offering the possibility to value the block geometry.
The basis for all calculations is a cross flight (RC), which consists of two separate partial flights. The image data format used in the following is an uncompressed TIF, which was derived from the recorded RAW image data with the Capture One software from Phase One. For the results shown in Figure 7, ONE set of calculated interior orientation parameter is introduced (UNIFIED – identical for both partial flights).



RMSE GCP - Phaseone IXU 1000 TIF / UNIFIED [mm]

	45 GCP	22 GCP	12 GCP	5 GCP
X-Error	2,0	2,5	2,9	3,1
Y-Error	2,5	3,0	3,1	3,8
Z-Error	4,5	5,1	6,2	6,3
3D-Error	5,5	6,4	7,6	8,0

RMSE CP - Phaseone IXU 1000 TIF / UNIFIED [mm]

	45 GCP	22 GCP	12 GCP	5 GCP
X-Error	n/a	1,3	1,9	2,4
Y-Error	n/a	2,2	3,1	4,7
Z-Error	n/a	5,1	5,9	8,2
3D-Error	n/a	5,7	6,9	9,7

RMSE GCP - Zenmuse X5S TIF / UNIFIED [mm]

	45 GCP	22 GCP	12 GCP	5 GCP
X-Error	2,8	2,4	2,9	5,1
Y-Error	3,7	4,3	4,6	7,1
Z-Error	6,4	6,7	8,4	0,4
3D-Error	7,9	8,3	10,0	8,8

RMSE CP - Zenmuse X5S TIF / UNIFIED [mm]

	45 GCP	22 GCP	12 GCP	5 GCP
X-Error	n/a	3,7	3,6	5,6
Y-Error	n/a	5,8	5,4	9,9
Z-Error	n/a	11,2	15,8	29,6
3D-Error	n/a	13,2	17,1	31,7

RMSE GCP - Phantom4PRO TIF /UNIFIED [mm]

	45 GCP	22 GCP	12 GCP	5 GCP
X-Error	2,4	3,1	4,1	5,9
Y-Error	3,6	4,4	5,0	6,4
Z-Error	4,4	4,3	4,9	3,9
3D-Error	6,2	6,9	8,1	9,6

RMSE CP - Zenmuse X4S TIF / UNIFIED [mm]

	45 GCP	22 GCP	12 GCP	5 GCP
X-Error	n/a	2,4	2,4	3,3
Y-Error	n/a	3,7	3,7	4,5
Z-Error	n/a	5,9	5,5	10,1
3D-Error	n/a	7,3	7,1	11,5

Fig. 7: RMSE values at GCPs (left) and CPs (right). Flight arrangement: RC. ONE set of interior orientation parameters (UNIFIED). Calculation: Agisoft PhotoScan. Note scaling.

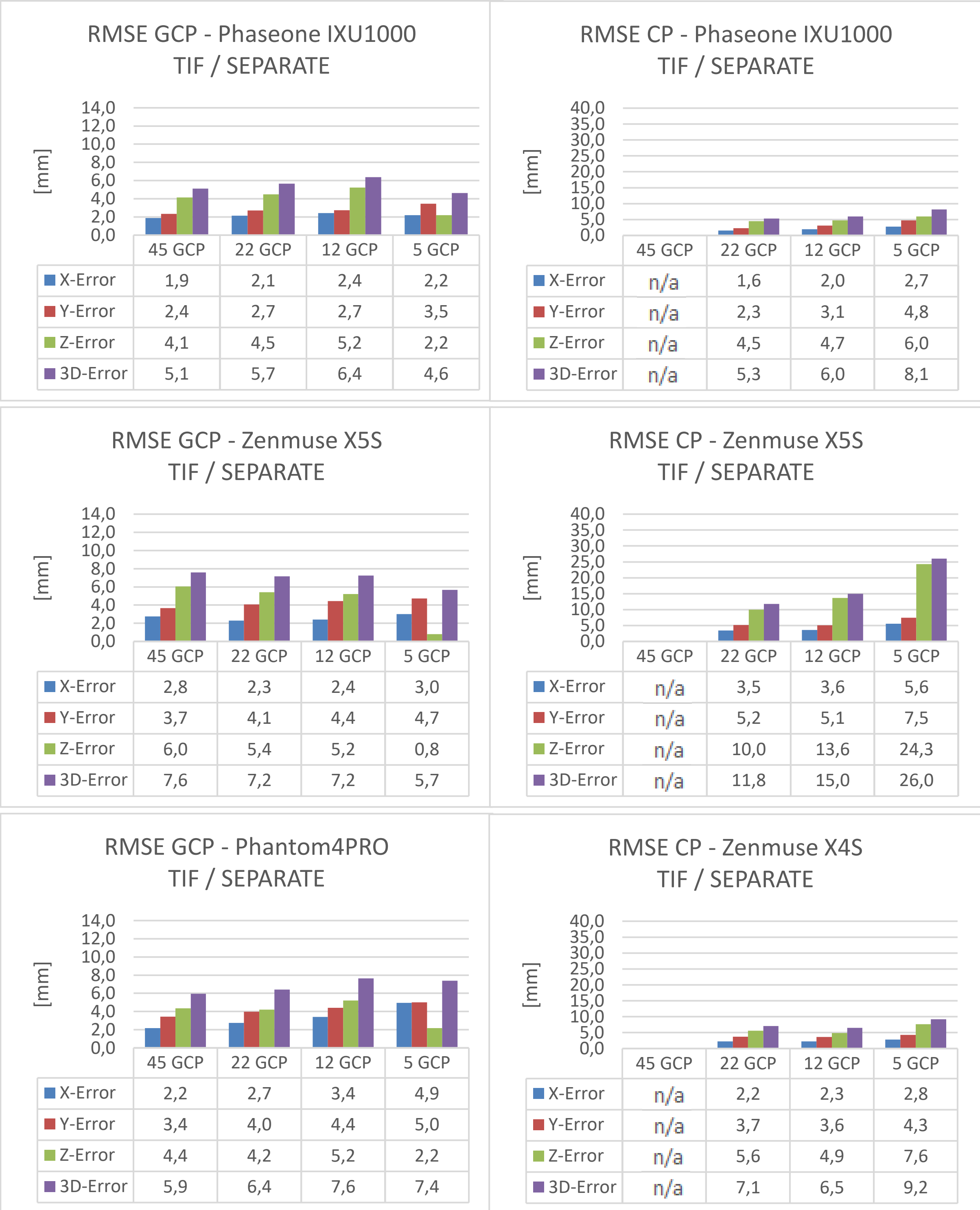
The comparison of the RMSE values at the control points (at which any existing model bending can be detected) shows significant differences between the different systems. The large-format Phase One camera system provides the lowest RMSE values – a result that can be confirmed for all control point arrangements.
Even in the minimum arrangement (5 GCP – in the block corners and the block center), this leads to 3D accuracies that are well below the GSD of 14 mm. Both, the large image format and the mechanical stability of the camera, are responsible for these results.
The Zenmuse X4S, the standard camera system of the Phantom 4 PRO (also usable with the Inspire 2) shows only slightly worse results. The 3D RMSE value is below the GSD, even with minimal ground control point distribution. The camera concept implemented in the Zenmuse X4S, comprising a fixed-focus lens and a mechanical central shutter, displays a high stability and shows – at least in the context of the flights carried out here in a timely manner – almost metric characteristics.
In contrast to the two other systems, the results for the Zenmuse X5S are significantly worse. The existing interchangeable lens in conjunction with the electronic focusing to infinity, lead to a camera system that is not very stable in itself, with mechanical clearance between lens and camera body at the bayonet. The RMSE values are 2-3 times worse than those of comparable systems and only lay below the GSD, when the control points are close together (here 22 GCP).

4.2 Effects of separate interior orientation parameters

The main reason for carrying out cross flights via separate flights is based on the fact that commercialy available flight planning tools (e. g. Map Pilot, Pix4DCapture) do not allow cross flights with varying flight altitudes. Besides that, RAW data storage in the DJI systems requires a reduction in flight speed to have sufficient time for storing images on the SD card (approx. a factor of 3 higher time requirement compared to the "DJI-JPG"). Storing images on the available and much faster SSD medium is not possible. It occurs that nobody – even DJI consultants – knows why! Consequently, a new setup must be carried out for the DJI systems before each flight, as these lose their settings temporarily after being without power due to the change of batteries.
This fact makes it reasonable to carry out the bundle block adjustment with separate interior orientation parameters for the partial flights within the scope of cross flights. The results are summarized in Figure 8. Although the results of the variants "RC UNIFIED" and "RC SEPARATE" are similar, it can be observed that the variant "RC SEPARATE" leads to increased accuracy, especially for the Zenmuse X5S. This tendency is a clear indication of the less stable interior orientation compared to the X4S and Phase One system.
Based on the reasons mentioned above (concerning the DJI system), it would make sense to be able to leave the cameras switched on, i.e. by using a buffer battery, upon changing of the power sources. In this case the setup would remain intact (unfortunately a previously unheard request from photogrammetric users to the DJI developers!).

4.3 Effects of single-flight arrangement

A complete cross flight usually represents a considerable additional effort over the entire process chain, starting from the recording to the final evaluation. When using metric cameras (typically: digital aerial cameras), however, this extended flight arrangement can be dispensed with.



RMSE GCP - Phaseone IXU1000, TIF / SEPARATE [mm]

	45 GCP	22 GCP	12 GCP	5 GCP
X-Error	1,9	2,1	2,4	2,2
Y-Error	2,4	2,7	2,7	3,5
Z-Error	4,1	4,5	5,2	2,2
3D-Error	5,1	5,7	6,4	4,6

RMSE CP - Phaseone IXU1000, TIF / SEPARATE [mm]

	45 GCP	22 GCP	12 GCP	5 GCP
X-Error	n/a	1,6	2,0	2,7
Y-Error	n/a	2,3	3,1	4,8
Z-Error	n/a	4,5	4,7	6,0
3D-Error	n/a	5,3	6,0	8,1

RMSE GCP - Zenmuse X5S, TIF / SEPARATE [mm]

	45 GCP	22 GCP	12 GCP	5 GCP
X-Error	2,8	2,3	2,4	3,0
Y-Error	3,7	4,1	4,4	4,7
Z-Error	6,0	5,4	5,2	0,8
3D-Error	7,6	7,2	7,2	5,7

RMSE CP - Zenmuse X5S, TIF / SEPARATE [mm]

	45 GCP	22 GCP	12 GCP	5 GCP
X-Error	n/a	3,5	3,6	5,6
Y-Error	n/a	5,2	5,1	7,5
Z-Error	n/a	10,0	13,6	24,3
3D-Error	n/a	11,8	15,0	26,0

RMSE GCP - Phantom4PRO, TIF / SEPARATE [mm]

	45 GCP	22 GCP	12 GCP	5 GCP
X-Error	2,2	2,7	3,4	4,9
Y-Error	3,4	4,0	4,4	5,0
Z-Error	4,4	4,2	5,2	2,2
3D-Error	5,9	6,4	7,6	7,4

RMSE CP - Zenmuse X4S, TIF / SEPARATE [mm]

	45 GCP	22 GCP	12 GCP	5 GCP
X-Error	n/a	2,2	2,3	2,8
Y-Error	n/a	3,7	3,6	4,3
Z-Error	n/a	5,6	4,9	7,6
3D-Error	n/a	7,1	6,5	9,2

Fig. 8: RMSE values at GCPs (left) and CPs (right). Flight arrangement: R+C. TWO sets of interior orientation parameters (SEPARATE). Calculation: Agisoft PhotoScan. Note scaling.

RMSE GCP - Phaseone IXU1000 TIF / R_ONLY

	45 GCP	22 GCP	12 GCP	5 GCP
X-Error	2,1	2,2	2,1	2,0
Y-Error	2,7	2,9	2,8	3,6
Z-Error	7,6	8,3	10,4	14,6
3D-Error	8,3	9,1	11,0	15,2

RMSE CP - Phaseone IXU1000 TIF / R_ONLY

	45 GCP	22 GCP	12 GCP	5 GCP
X-Error	n/a	2,3	2,5	2,7
Y-Error	n/a	2,9	3,8	5,3
Z-Error	n/a	11,7	10,9	10,4
3D-Error	n/a	12,3	11,8	12,0

RMSE GCP - Zenmuse X5S TIF / R_ONLY

	45 GCP	22 GCP	12 GCP	5 GCP
X-Error	2,7	2,6	2,3	1,5
Y-Error	3,7	4,2	4,6	4,3
Z-Error	4,0	3,1	2,5	0,7
3D-Error	6,0	5,8	5,7	4,6

RMSE CP - Zenmuse X5S TIF / R_ONLY

	45 GCP	22 GCP	12 GCP	5 GCP
X-Error	n/a	4,7	5,5	12,6
Y-Error	n/a	5,8	8,5	29,4
Z-Error	n/a	11,0	11,2	289,5
3D-Error	n/a	13,3	15,1	291,2

RMSE GCP - Phantom4PRO TIF / R_ONLY

	45 GCP	22 GCP	12 GCP	5 GCP
X-Error	2,4	2,5	2,3	3,9
Y-Error	3,7	4,3	4,2	4,3
Z-Error	5,1	4,6	5,3	2,7
3D-Error	6,7	6,8	7,1	5,8

RMSE CP - Zenmuse X4S TIF / R_ONLY

	45 GCP	22 GCP	12 GCP	5 GCP
X-Error	n/a	2,9	3,1	3,6
Y-Error	n/a	4,1	4,2	4,9
Z-Error	n/a	7,7	7,4	11,5
3D-Error	n/a	9,2	9,0	13,0

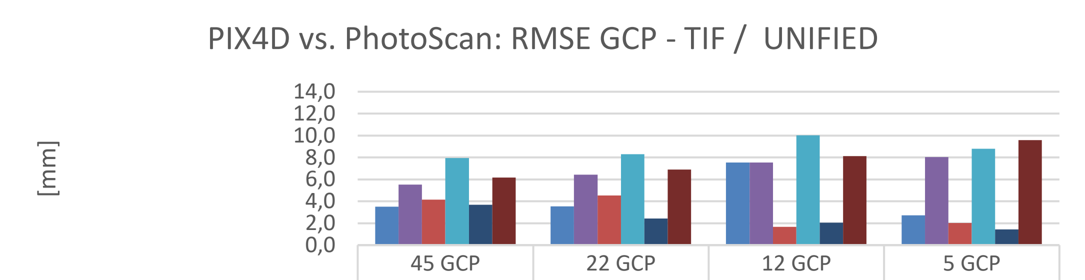
Fig 9: RMSE values at GCPs (left) and CPs (right). Flight arrangement: R. Calculation: Agisoft PhotoScan. Note scaling.

The effects of a single flight (here: Regular – R) on the examined UAV cameras appear to be very clear (Figure 9). While the mechanically more stable systems – Phase One and Zensmuse

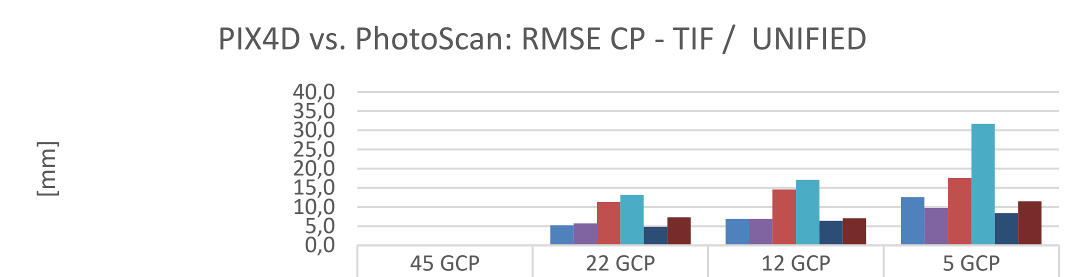
X4S – tend to display poorer results (in comparison to the cross-flight configuration), the Zenmuse X5S shows significant losses in accuracy. Particularly affected is the height accuracy in conjunction with a reduced number of control points for the block referencing. The larger RMSE values (in Z-direction) result mainly from problems with the numerical determination of the parameter "focal length", for which the present R-block obviously offers minor depth information.
Beyond that, the positive effect of a very dense arrangement of control points is clearly visible in this block for the instable X5S. The results of the large-format Phase One are almost independent of the control point distribution, as can be seen from the RMSE values of the control points (CP). In principle, this observation also applies to the Zenmuse X4S.

4.4 Comparison of the software products used

The number of software products used to generate image-based point clouds is constantly increasing. Although it can be assumed that users of a certain company/organisation work with the same software, the photogrammetric community naturally uses different software applications in everyday life, which often do not lead to identical results.
Therefore, based on the Zollern test data sets, identical projects using the Agisoft PhotoScan (Agisoft 2018) and Pix4Dmapper (Pix4D 2018) software were performed. Both software programs are commercial products and have a considerable market presence.
The configuration of the created projects corresponds to the specifications for the respective software. As far as available, implemented "templates", with standard parameters, were used. The measurement of the signalized ground control points was carried out manually by the same operator, based on the measurement routines preinstalled in the programs.
For this reason, the herein presented approach can be regarded as representative for project work. Thus, the resulting results are largely unaffected by "extended expert knowledge".
Figure 10 shows the three-dimensional RMSE values after the bundle block adjustment, whereby a separate representation of position and height deviations is omitted here. The differences of the RMSE values are clearly visible for all examined cameras and the respective block references. In general, the calculations with Pix4Dmapper tend to result in significantly lower RMSE values than in the comparative projects which were carried out with Agisoft PhotoScan. This applies to the ground control points (GCP) as well as to the control points (CP). Basically, it is difficult to find reasons for this, since technically the same methods are utilized. In contrast, different procedures can be assumed within the software, which, however, are less likely to be evaluated by users.
Despite this fact, the results shown in Figure 10 are of some relevance, as they represent one of the essential evaluation criterions for image orientation. Particularly in the context of engineering projects, which require an accuracy level of just a few millimeters, a quality assessment of the results achieved is rather difficult (e.g. concering the question wether a defined accuracy has been reached).



	45 GCP	22 GCP	12 GCP	5 GCP
PhaseOne IXU 1000 (PIX4D)	3,5	3,5	7,6	2,7
PhaseOne IXU 1000 (PS)	5,5	6,4	7,6	8,0
Zenmuse X5S 15 mm (PIX4D)	4,2	4,5	1,7	2,0
Zenmuse X5S 15 mm (PS)	7,9	8,3	10,0	8,8
Phantom4PRO (PIX4D)	3,7	2,4	2,0	1,4
Phantom4PRO (PS)	6,2	6,9	8,1	9,6



	45 GCP	22 GCP	12 GCP	5 GCP
PhaseOne IXU 1000 (PIX4D)	n/a	5,2	6,9	12,6
PhaseOne IXU 1000 (PS)	n/a	5,7	6,9	9,7
Zenmuse X5S 15 mm (PIX4D)	n/a	11,3	14,6	17,5
Zenmuse X5S 15 mm (PS)	n/a	13,2	17,1	31,7
Phantom4PRO (PIX4D)	n/a	4,8	6,4	8,4
Phantom4PRO (PS)	n/a	7,3	7,1	11,5

Fig. 10: Comparison of the 3D RMSE values at GCPs (top) and CPs (bottom) as results of the bundle block adjustments with PIX4Dmapper and Agisoft PhotoScan. Note scaling.

5. CONCLUSION & OUTLOOK

The in-situ tests of various UAV systems carried out on the basis of comparable data sets of the UAV test field at the Zollern colliery revealed noticeable differences in the performance of the cameras used. Suprisingly, the cheapest camera in the test, the Zenmuse X4S, yielded remarkable good results.

Furthermore, the positive effects of cross flights (with differences in flight altitude of approx. 20%) were confirmed. Unfortunately, the flight planning tools do not generally offer this variant as a standard concept, so that there should be a certain need for action on the supplier's side. This is accompanied by the necessity of self-calibration for the cameras used. None of the examined cameras can be described as a metric camera under consideration of the specific requirements coming from a high-precision UAV image flight. Taking into account the individual camera concept, it can therefore also make sense to introduce partial flights, with their own parameters of interior orientation, into the bundle block adjustment.

The final comparison of the calculated results using different software products, is in some way astonishing, as it shows clear differences in quality (accuracy) within the available data sets. This is where further investigations (also by the software providers) should start.

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