Calibration Low-Cost Cameras with Wide-Angle Lenses for Measurements

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Abstract:
So far too many examinations concerning the possibility of the application action cameras weren't conducted in UAV photogrammetric studies. However in the recent time development of the action cameras production technology he let receive sensors which are light, user-friendly, and most importantly can gain images and video sequences of high resolution. The essential meaning has taking into account the camera's influencing factors in UAV photogrammetry. Due to the fact that the action cameras are non-metric cameras the significant influence on the quality of photogrammetric studies has a stability internal orientation of elements of such cameras. Within the framework of carried out research calibration of five GoPro Hero 4 Black. The calibration of cameras was carried out on different calibration tests in the GML Camera Calibration Toolbox and Agisoft Lens software. Different calibration setups and processing are presented and discussed in this article. Additionally a repetitiveness of achieved results of the calibration was examined in five GoPro cameras Hero 4 Black. Dedicated calibration templates in the form of chessboards were used to the calibration. As a part of the research a comparative analysis of the results have been done. Based on performed examinations a repetitiveness of determined internal orientation elements was checked under different video acquisition modes.

Keywords: *sensors, measurements, camera calibration, videos, accuracy*

1. Introduction

Increasing the availability of high-resolution (4K resolution and more) action cameras such as GoPro Hero 4 equipped with wide angle lens (fish-eye) caused the noticeable height of applying sensors of this type in UAV photogrammetry. Applying cameras of this type is much more difficult in the relationship to non-metric compact cameras. Broad field-of-view of assembled lenses in action cameras very often cause difficulty in the accomplishment of calibration of such camera and this her determination of reliable elements of internal orientation. Standard wide-angle lens (fish-eye lens) assembled in action cameras are characterized by short lengths of focal lengths and high radial distortions. So far in UAV photogrammetry dominated non-metric amateur cameras [1], [2], [3], [4], [5] which were equipped in low cost lens low-class. Carrying out the calibration of such cameras equipped with normal angle lens very often didn't provide the internal orientation elements for the repetitiveness of this elements. In case of action cameras with wide-angle lenses determination of internal orientation elements can be even more difficult [6]. Non-metric cameras calibration lets appoint elements of the internal orientation to the purpose of extract accurate 3D metric information from their images [7]. Parameters that is determined are: calibrated focal length (c_k) of the lens, the coordinates of the center of projection of the image (x_p, y_p), the radial lens distortion coefficients (K_1, K_2, K_3) [8] and tangential distortion coefficients (P_1, P_2). Therefore it is recommended to pre-calibration action cameras in order to ensure reliable elements of internal orientation to allow for precise photogrammetric reconstructions. The calibration of cameras and the evaluation of the high credibility of appointed elements of the internal orientation are still main and with point at issue in the area of research of the development of photogrammetry [9] including UAV photogrammetry. Unknown internal geometry is a main problem in sensors equipped with wide-angle lenses [10], [11]. The full review of camera calibration methods and models became encompassed in many the publications [9], [12], [13]. Results included in above articles constitute specific summing up experience associated with using digital cameras to the photogrammetric measurement. It was then presented in interpretation of different configurations, parameters and analysis techniques of the cameras associated with the calibration. They also presented well-known photogrammetric systems from implemented models of the calibration of cameras and increasing 3D accuracy algorithms through the self-calibration bundle adjustment. The issues associated with the calibration of cameras in the recent time also became a research topic in Computer Vision (CV) field. Research assembles on full automatism of the process of calibration [14] on the basis of linear approaches with simplified imaging models [15]. The first works above these methods concerned pinhole camera model and included the modelling radial distortion [16], [17], [18]. At present algorithms of the calibration of cameras were broadened by libraries open source ready answers e.g. OpenCV containing already ready solutions. These algorithms are based on detecting the substantial amount of points on the flat test field of the type chessboard [19], [20]. However the use of flat objects for camera calibration does not provide such high accuracy as 3D test fields. However in most applications applying 2D test fields of type chessboard is acceptable [21], [22]. In the photogrammetric presentation the camera calibration can be above methods regarded acceptable. Correct designing measurements, correct photographing calibration tests and achievement image measurement and bundle adjustment let to carry out the accurate and correct calibration for the majority of compact digital cameras. Research relating to photogrammetric measurements with the wide-angle lenses application are carried out from several years [23]. The pictures obtained with the use of such lenses require preceding of processing approach. The imaging process is not compatible with a central projective model. It is necessary made of the preliminary corrections of distortions caused by the large impact of the distortion. In the other approach it is possible to implement wide-angle lens model in self-calibration. Many researchers proposed the various procedures associated with the calibration of this type of cameras [6], [23], [24] they were primarily based on the geometry of the epipolar line and equidistant rectification of distorted images to be applied to central projective. In case of calibration procedures it is possible to adopt the assumptions similar to the calibration action cameras like GoPro Hero 4 which are equipped in wide-angle (fisheye) lenses. To this time several research work related to the calibration and application of these cameras in the photogrammetric perfected has been carried out [8], [25], [26]. In above articles results relating to calibration of the GoPro Hero 3 and GoPro Hero 4 cameras and of their uses to photogrammetric goals were discussed. On the basis of research it is recommended to use the highest possible resolution and where a high accuracy of applying 3D calibration field is necessary. Procedures of the calibration were based on algorithms from OpenCV and comparative analyses with the Agisoft Lens software. 2D and 3D calibration field were applied to calibration. In another approach [26] proposed a calibration procedure for the sequential method where the approximate elements of the orientation of an internal were treated as first value. Applying of action cameras for the completion of photogrammetric studies was also discussed in [25], where the Agisoft Photoscan software and Photomodeler were used to the extraction of the thick cloud of points from video frames. The results of research assembling on the calibration procedures of five cameras GoPro hero 4 Black applied - photogrammetric tests are presented in this article. Within the framework of research various procedures of the calibration of cameras were presented in order to estimate the stability of elements of internal orientation. In the framework of the research work calibrations of five cameras were performed. Each calibration has been carried out in the five measurement series in software Agisoft Lens and Camera Calibration Toolbox. The obtained results have been analyzed for their stability. The whole of the article was divided in five parts, and at the end a list of literature was put.

2. Camera Calibration – Mathematical Model

Camera calibration is intended to reproduce the geometry of the projection of the center on the basis of photographs of this camera. The calibration of the camera are:

- calibrated focal length – c_k;
- the position of the center of the views in relation to the pictures, determined by x_0 i y_0 – image coordinates of the principal point;
- distortion of lens – factors of radial distortion: K_1, K_2, K_3 and tangential: P_1, P_2.

In case of action cameras they have one large FOV in wide angle viewing mode. In this case the calibration process plays a very important role in order to model distortion in the lens. Model of internal orientation in the photogrammetric presentation applied in researches computer vision Agisoft Lens, Camera Calibration Toolbox and Open CV based on a modified mathematical of the Brown Calibration model [27].

Parameters of the distortion are determined in the relationship of the principal point. Character of the radial distortion depends on the structure of lens and situating the aperture in it. The value of the distortion depends on the angle α and lengths of the ray r:

$$\Delta r = r - c_k \cdot \mathrm{tg}\alpha \tag{1}$$

where:
Δr – the size of the radial distortion
r – radial distance;
c_k – calibrated focal length;
α – field angle.

Course of the crooked radial distortion approximate is through the polynomial odd power lengths of the ray [28]:

$$\Delta r = K_1 r^3 + K_2 r^5 + K_3 r^7 + \ldots \tag{2}$$

where:
K_1, K_2, K_3 – polynomial coefficients of radial distortion;
r – radial distance.

$$r = \sqrt{\left(x - x_0\right)^2 + \left(y - y_0\right)^2} \tag{3}$$

where:
x, y – image coordinates of the point related to fiducial center;
x_0, y_0 – image coordinates of the principal point.

Tangential distortion (otherwise non-metrical, asymmetric) it is a distortion consisting in the fact that images of straight lines going through the principal point of the image aren't straight [27]:

$$\begin{aligned}\Delta x_{\tan} &= P_1\left(r^2 + 2\overline{x}^2\right) + 2P_2\overline{xy}\\ \Delta y_{\tan} &= P_2\left(r^2 + 2\overline{y}^2\right) + 2P_1\overline{xy}\end{aligned} \tag{4}$$

where:
$\Delta x_{\tan}$, $\Delta y_{\tan}$ – the effect of tangential distortion for image coordinates $\overline{x}, \overline{y}$;
$\overline{x}, \overline{y}$ – image coordinates of point before the correction related to the principal point;
P_1, P_2 – coefficients describe the impact of tangential distortion.

3. The Experiment

3.1. Cameras Specification

In carried out research five GoPro Hero 4 Black cameras were used (Fig. 1) equipped with wide-angle lens and rolling shutter. The CMOS sensor is reading images by rows.

Fig. 1. Five cameras GoPro 4 Hero Black

GoPro 4 camera can work in camera and video modes. In these possible arrangements is also possible the use of different dividedness and the speeds of recording of the sequence of video with the different FOV. Record videos in 4K/30fps modes in ultra-wide FOV combination up to 170°, 2.7K/50fps and Full HD/120fps. The camera has also a fast serial mode allowing for taking up to 30 pictures (12 megapixels) per second [28]. Table 1 shows technical specification.

Table 1. Technical specification GoPro 4 Hero black

Item	Description
Size [mm]	41 × 59 × 30
Weight [g]	88
Optical sensors type	CMOS
Digital Video Format	H.264
Nominal focal length [mm]	3
Image Recording Format	JPEG
Max Video Resolution	3840 × 2160
Effective Photo Resolution	12.0 MP
Sensor size [mm]	6.16 × 4.62
Pixel pitch [μm]	1.55

Additionally at present sensors of the video are deprived of mechanical systems of the shutter for electronic rolling shutters.

3.2. Cameras Calibration

2D and 3D calibration tests are most often used for the calibration of nonmetric cameras. As part of research works two different calibration tests of type 2D were used based on the pattern chessboard and equation Brown and Brown equation adopted in Agisoft Lens and Camera Calibration Toolbox. Both software packages based on similar mathematical models, but various algorithms. Agisoft Lens software uses to calibration flat test field shown on the display screen (Fig. 2) and offer fish-eye camera models, too.

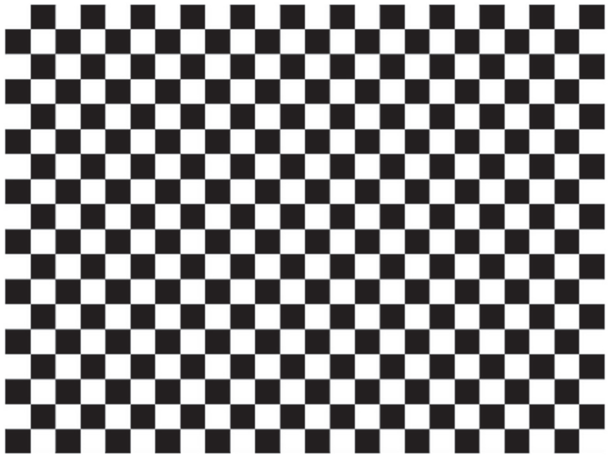

Fig. 2. Agisoft Lens 2D calibration field [31]

Video sequences were registered under different angles from the same distance. Video they recruited under five different angles: from the front, from right, from left, from above and from the ground floor. During the recording of the image a condition was preserved so that the pivot of lens of every of cameras proceeded through the focal point of the test. GML Camera Calibration Toolbox software has been developed in order to determine the elements of the internal orientation of non-metric digital cameras. It is based on algorithms of the calibration of the image from the OpenCV library. The following parameters are determined in calibration process: calibrated focal length c_k, principal point coordinates x_0, y_0, radial distortion coefficients: K_1, K_2 and tangential distortion coefficients: P_1, P_2.

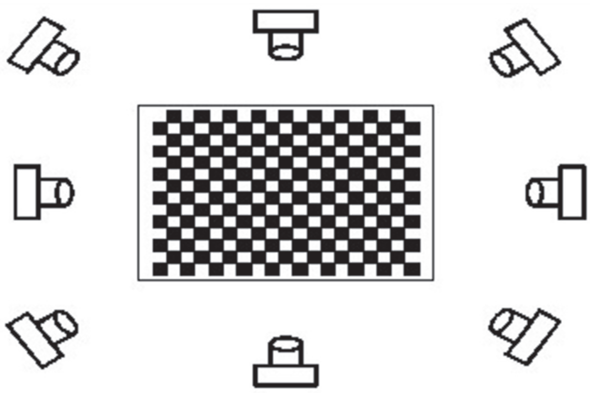

Fig. 3. GML Camera Calibration Toolbox chessboard calibration field – camera positions [30]

Test field resembling the chessboard is applied to calibration (Fig. 3) The test consists of squares: white and black which are arranged alternately. Square size is 3-5 cm. One side should contain the even number of squares, and second odd. Calibration patterns using odd x even (or even × odd) number of squares (i.e 5 × 6, 7 × 8, 10 × 7, etc). Calibration sheet should be in the form of a rectangle. This makes it possible to specify the orientation of the design. The chessboard on the images must be located in the all places of the camera matrix [29]. Evaluation of the results of calibration cameras was based on statistical analyses and comparative analysis between individual cameras. As the action cameras usually have large FOV in wide viewing mode, camera calibration plays an important role to calibrate the effect of lens distortion before image matching. A black and white chess box pattern and Brown equation are adopted in camera calibration. Once the cameras has been calibrated, the author use these action cameras to take video in an indoor environment. The videos are further converted into multiple frame images based on the frame rates.

4. Calibration Results and Discussion

Images data taken by five GoPro Hero4 cameras in different acquisition modes. As part of research works a calibration of cameras was carried out for the 2.7K video mode and 4K Wide video. In this research video mode were used to record the chessboard field at different view angles and positions. Video frames are converted to single picture at 1 image per second. For each action camera five measuring series were carried out taking into consideration accomplishment in each series the accomplishment of minimum of five frames in the different locations of the camera. During carrying out the video sequence similar measuring conditions were ensured for acquired samples for most accurate results. The results of internal orientation for five cameras for the 2.7K and 4K Wide video mode in Agisoft Lens software were presented in Table 2 and Table 3. Results of camera calibration in GML Camera Calibration Toolbox (CCT) software were presented in Table 4 and Table 5.

Within the framework of research five action cameras calibration result were in video-mode. Obtained results in both variants of calibration for the 2.7K mode are comparable. Determined calibrated focal length values on average differs about 0.3 mm from given value by the producer.

However calibrated focal length and principal point coordinates are comparable with other test results [6]. They also observed that results of the calibration of cameras in the Agisoft Lens software were repeatable for the calibration of every of five cameras. In case of the calibration in the GML Camera Calibration Toolbox software (CCT) such a dependence was not observed. Probably because this software is using various algorithms of the calibration leaning on modified OpenCV towards Agisoft Lens which also has algorithms adapted to the calibration fish-eye lens.

Table 2. Calibration results for five cameras for 2.7K video GoPro 4 Hero Black mode based on Agisoft lens

Parameter	CAM 1		CAM 2		CAM 3		CAM 4		CAM 5	
	Mean value	σ	Mean value	σ	Mean value	σ	Mean value	σ	Mean value	σ
c_k [mm]	2,70	0,015	2,70	0,001	2,77	0,025	2,72	0,041	2,79	0,019
x_0 [mm]	0,144	0,074	0,150	0,003	0,145	0,050	0,130	0,041	-0,297	0,008
y_0 [mm]	-0,056	0,007	0,024	0,005	0,096	0,051	0,069	0,076	0,025	0,107
K_1	4,56E-04	2,31E-06	4,59E-04	3,72E-08	4,62E-04	2,26E-06	4,61E-04	1,36E-06	4,56E-04	1,42E-06
K_2	2,70E-07	1,87E-08	2,89E-07	9,72E-10	2,65E-07	1,98E-08	2,57E-07	1,21E-08	2,80E-07	1,18E-08
K_3	3,86E-11	3,98E-11	1,75E-11	2,73E-12	3,10E-11	4,88E-11	1,06E-10	2,85E-11	3,51E-11	2,60E-11
P_1	6,00E-05	3,49E-05	-3,46E-05	1,00E-06	9,87E-05	3,29E-05	2,91E-05	2,44E-05	5,68E-05	1,30E-05
P_2	3,46E-06	4,85E-06	-6,34E-05	2,54E-06	-3,42E-04	3,09E-05	6,04E-05	5,00E-05	-1,85E-04	6,49E-05

Table 3. Calibration results for five cameras for 4K video GoPro 4 Hero Black based on Agisoft Lens

Parameter	CAM 1		CAM 2		CAM 3		CAM 4		CAM 5	
	Mean value	σ	Mean value	σ	Mean value	σ	Mean value	σ	Mean value	σ
c_k [mm]	2,77	0,035	2,83	0,027	2,72	0,043	2,77	0,011	2,76	0,027
x_0 [mm]	0,825	0,068	-0,288	0,012	0,236	0,022	-0,213	0,005	-0,108	0,016
y_0 [mm]	-0,729	0,058	0,283	0,023	0,571	0,081	0,414	0,039	0,221	0,009
K_1	9,27E-04	5,01E-06	9,26E-04	1,22E-06	9,37E-04	3,98E-06	9,22E-04	3,01E-06	9,40E-04	1,36E-06
K_2	8,26E-07	4,38E-08	9,75E-07	6,29E-09	8,65E-07	5,96E-08	9,02E-07	1,28E-07	7,80E-07	4,16E-09
K_3	1,47E-09	1,14E-10	1,20E-09	1,71E-11	1,49E-09	1,96E-10	1,18E-09	9,73E-11	1,69E-09	8,43E-12
P_1	3,76E-05	9,27E-05	-1,41E-04	2,27E-05	-2,24E-04	2,45E-05	-4,83E-05	2,19E-05	1,39E-04	2,46E-05
P_2	2,41E-04	9,10E-05	2,74E-04	3,77E-05	1,79E-04	1,39E-04	2,93E-05	3,03E-05	-1,18E-06	1,46E-05

Table 4. Calibration results for five cameras for 2.7K video GoPro 4 Hero Black based on camera calibration toolbox

Parameter	CAM 1		CAM 2		CAM 3		CAM 4		CAM 5	
	Mean value	σ	Mean value	σ	Mean value	σ	Mean value	σ	Mean value	σ
c_k [mm]	2,68	0,007	2,67	0,009	2,72	0,008	2,72	0,044	2,79	0,038
x_0 [mm]	0,135	0,103	-0,132	0,002	0,139	0,002	0,149	0,005	-0,269	0,003
y_0 [mm]	0,065	0,290	-0,048	0,002	0,070	0,004	0,079	0,009	0,019	0,005
K_1	4,04E-04	6,44E-06	4,05E-04	6,71E-04	4,02E-04	1,33E-04	4,04E-04	-6,63E-04	4,10E-04	6,65E-05
K_2	2,06E-07	3,59E-08	3,03E-07	-1,29E-08	2,08E-07	2,12E-08	2,12E-07	1,46E-07	2,10E-07	1,47E-07
K_3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P_1	6,37E-05	5,87E-05	4,65E-05	-2,56E-05	3,67E-05	9,95E-10	-2,92E-05	-2,18E-06	7,27E-05	-1,04E-07
P_2	2,48E-06	3,61E-07	-4,65E-05	2,85E-05	-1,66E-04	5,04E-09	3,35E-04	-2,78E-04	-8,98E-05	-2,20E-07

Table 5. Calibration results for five cameras for 4K video GoPro 4 Hero Black based on camera calibration toolbox

Parameter	CAM 1		CAM 2		CAM 3		CAM 4		CAM 5	
	Mean value	σ	Mean value	σ	Mean value	σ	Mean value	σ	Mean value	σ
c_k [mm]	2,80	0,177	2,81	0,012	2,79	0,016	2,76	0,054	2,74	0,019
x_0 [mm]	0,800	0,014	-0,289	0,005	0,204	0,025	-0,196	0,005	-0,102	0,002
y_0 [mm]	-0,700	0,039	0,261	0,003	0,533	0,014	0,414	0,004	0,227	0,003
K_1	9,17E-04	6,39E-06	9,12E-04	6,47E-05	9,05E-04	6,48E-03	9,96E-04	-6,65E-05	9,23E-04	-6,50E-05
K_2	1,42E-05	1,88E-05	9,53E-07	1,40E-07	8,58E-07	1,40E-05	-9,73E-07	1,47E-07	9,40E-07	1,41E-07
K_3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P_1	3,63E-05	2,75E-06	4,44E-05	-6,53E-10	1,27E-04	2,97E-09	4,65E-05	-1,19E-07	5,45E-05	1,94E-10
P_2	2,26E-04	7,14E-05	2,31E-04	-1,74E-08	-2,00E-04	2,77E-08	2,78E-05	-2,27E-07	1,71E-05	-3,40E-08

In the case of the results obtained for the 4K video discrepancies for determined external orientation elements are much bigger especially in the case of values assigned to the distortion also appearing differs in sign. The calibration of cameras in 4K Wide mode is showing the instability of determined elements of the internal orientation, where FOV for this mode of up to 170°. These differences can result from restrictions of the GML CCT software for wide-angle lens calibration, due to the fact that in the calibration process the radial distortion parameters K_3 values are not determined, which are important in case of calibration of cameras with a large FOV like GoPro Hero 4. Therefore one should cautiously approach comparing distortion parameters, because by the applying various calibration parameters by software it is difficult. The results of other research show that the calibration of camera using OpenCV differs most compared to the others.

5. Conclusions

Results of calibration and their quality for five action cameras – GoPro Hero 4 Black of two calibration methods in Agisoft Lens Software and GML Camera Calibration Toolbox are presented in this article. Applying different display modes and algorithms of the calibration allowed to investigate stability of elements of internal orientation of cameras with an ultra-wide FOV. Obtained results described the instability of the elements of internal orientation in the mode of wide-angle even for the principal point. Therefore one should assume that achieved results are only partly comparable with oneself.

Repeatable results of the calibration were achieved for the 2.7 K Video mode in the Agisoft Lens software. This confirms that these cameras can be successfully used in photogrammetric applications. Slightly worse repeatability were obtained for 4K ultra-wide FOV mode. Calibration cameras results in the GML Camera Calibration Toolbox are less repeatability.

Future researches will concern the influence of use pre-calibrated interior orientation in receiving pre-corected images and for examining their accuracy potential in photogrammetry applications

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