The Proposal of Determining the Focal Length of a Non-Metric Digital Camera for UAV

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Abstract. Unmanned Aerial Vehicle - UAV, commonly referred to as drones are vehicles unique in the field of mechanics that can fly in the air without a human operator on board. In recent years, they have become a new interdisciplinary area of science and research. Because they combine photogrammetry, aviation engineering, navigation and automation. Modern UAVs are synchronized with GNSS signals and are remotely piloted or carry out autonomous flights. They can simultaneously perform very complex operations for the implementation of many different civil and military tasks. Currently, drones play an increasingly important role in the modern battlefield and are therefore included in the equipment of all modern world armies. They also find a great potential in civil applications. They are used in many fields of economy, technology and science. Acquiring geoinformation from unmanned aerial vehicles is currently used in the work of many services related to the functioning of the state. In the geomatics, the UAV platforms equipped with specialized sensors, are used to acquire images and photogrammetric and remote sensing data. Photogrammetric projections made by UAV are currently used to generate orthophotomaps, among others for the needs of cadastre. As we know, cadastral measurements, due to their importance, require high accuracy and reliability. They can only be guaranteed by correctly and precisely determined calibration parameters of non-metric cameras. The paper presents a method of determination of the focal length, of a digital non-metric photogrammetric camera. The experimental tests carried out confirmed the usefulness of the proposed calibration method carried out in laboratory conditions.

1. Introduction
Nowadays, digital non-metric cameras are actively used to solve digital photogrammetry tasks. Due to mass production, they are widely represented in the market and their cost is relatively low. Compactness, operability, mobility and accessibility are the main advantages of digital non-metric cameras. However, the technical documentation of non-metric cameras does not actually contain information about interior orientation elements (IOE) and distortion. Besides, their application without periodic calibration is impossible. Therefore, it is necessary to develop methods for determining these parameters with the appropriate precision. A large number of research methods for digital cameras (DC) in laboratory and field conditions are proposed at present time. Let’s analyze some of them in more detail. Publication [1] presents methods of calibrating high-resolution digital camera based on different configuration which comprised of stereo and convergent. The aim of the calibration was to investigate the behavior of the internal digital camera whether all the digital camera parameters such
as focal length, principal point and other parameters. In study, a non-metric digital camera called Canon Power Shot SX230 HS was calibrated in the laboratory and in the field using different configuration for data acquisition. Laboratory calibration was based on a 3D test field where a calibration plate of dimension 0.4m x 0.4m with grid of targets at different height is used. For field calibration, unmanned aerial vehicle (UAV) system was using for the same concept of 3D test field which comprised of 81 target points located on a flat ground and the dimension is 9m x 9m. All the images were processed using photogrammetric calibration software. The accuracy of the results was evaluated based on standard deviation. In general, it was found that the standard deviation of focal length improves well as the height increases. For stereo configuration, the result showed that this configuration was not suitable for camera calibration. So, authors recommend choosing the best method of calibration depends on the type of applications. Field methods for digital cameras calibration are also used in studies [2, 3]. Two ways of cameras calibration for controlling the results are proposed. The first method is based on the using of flat polygon for the complete camera calibration, including determination of IOE and exterior orientation elements (EOE), distortion parameters and the impact of atmospheric errors. The second way allows to perform a partial calibration of the camera, where only the focal length is determined. This method is called the two-level calibration and means the simultaneous using of the conditions of collinearity and the equality of heights differences of multi-scale images.

It should be noted that the first method has unquestionable advantages: no need to require two-level surveying, no limitations in the number and scale of images. However, in this case, the calibration parameters entirely depend on the coordinates of centers projection of images. The precision of which is determined by the error of satellite antenna coordinates and the errors of fixing the elements of the antenna reduction. At the same time, the results of the second method showed that the method allows obtaining the parameters of calibration with the necessary accuracy. The authors recommend processing the measurements sequentially by methods of full and partial calibration. After analyzing the work, it should be accentuated that it is necessary to set the initial values of the IOE (not equal to zero) in the experiment. Also, experimental research work was carried out only for mock-up photos.

In the work [4] for solving the problem of cameras calibration was developed and used specialized software. All calibration parameters are determined as a result of the multiple solution of the inverse problem of photogrammetry. The method of least squares with redundant measurements also applies to data processing. The authors admit that this approach ensures high accuracy of the definitions of the calibration parameters. During the calibration such parameters was defined: focal length, coordinates of the main point, distortion parameters. The results of the research, as noted by the authors, demonstrate the reliability of the used methods for calibrating. However, the error of photogrammetric measurements after processing the images is approximately 1 mm, which is not permissible.

The use of software for camera calibration is considered in the papers [5, 6, 7]. The publication [5] presents the results of a modified calibration method for the calculation of the interior orientation of digital consumer cameras. With a two-dimensional calibration field and the use of the CameraCalibrator 4.0 and PhotoModeler 4.0 software from EOS Systems Inc. an efficient and fast calculation method has been applied. The calibration results of the digital cameras Olympus E-10 and Nikon Coolpix 990 have been verified by repeated calibrations and the additional adjustment with the bundle adjustment software CAP. Eight photos have been taken of the test field with each camera. 42 tie points have been measured with subpixel accuracy with Photomodeler's automatic target marking function. In this research, the calculated differences between the measured distances and the control distances have been determined for all three cameras. As noted by the authors, the mean absolute differences between 0.038 and 0.064 mm was very good results for the tested cameras. However, for such calibration is need a suitable surface for the polygon construction, also, obtaining images with a sufficient variety of camera's inclination angles was a problem.
In papers [6] considered a similar field calibration method of a non-metric digital camera. It was conducted at an open space paved with no special targets for an amateur application. They concluded that the calibration method proposed was useful for some nonprofessional fields. The simplicity of the lab calibration with a flat grid pattern represents the highest advantage of this calibration method. [7] also used a flat pattern to calibrate a camera. Besides the simplicity of this method, the necessary equipment’s are only the calibration pattern, the digital camera and a tripod to ensure stability. The lower accuracy found in lab calibration might be due to the automatic process that generates more errors than with the manual process used in the field calibration.

Studying the effect of some image enhancement features on the accuracy of close-range photogrammetric measurements using CAD environment is presented in [6]. Eight of image enhancement feature were studied: re-size, sharpen, blur, midtone, contrast, highlight, shadow, and brightness. The original images were created using 3D studio MAX as a CAD environment. The results were statistically analyzed to find out the effect of the image enhancement features on the accuracy. The authors note that applying some of image enhancement features have the effect of measuring accuracy and some have no effect at all. After analyzing works in which the various software used to calibrate the cameras is worth highlighting the PhotoModeler package. The management of PhotoModeler for automatic calibration is very simple, and its cost is relatively low, compared to other software for calibrating digital cameras. However, the use of software means processing and converting images, which may lead to some misrepresentation.

The publication [8] examines the calibration parameters of digital non-metrical cameras and the requirements that must be met to obtain quality materials. The author notes that in the passport of digital cameras does not specify a range of focal lengths, but a range of segments within which the camera lens can move to get a sharp image. The work also presented formulas for determining such segments length and focal length. The paper [9] presents the process, the results and the accuracy of two calibrations methods. The first one consists in a lab calibration with a grid pattern and the second one, a field calibration, were the targets were draw in a flat surface. Photomodeler Scanner software was used for both calibration methods. The calibrated parameters obtained were: focal length, format size of the CCD sensor, location of the principal point sensor, two radial distortion function coefficients and two decentering distortion function coefficients. In this study, the lab calibration has a final total error of 1.940 pixels, which was a bit higher than the recommended. The field calibration has a total error of 0.282 pixels, which is assumed to be a very good calibration project.

The method of determining the focal length of non-metric digital camera was proposed in works [10, 11]. According to the method, digital images of a mirror test object were obtained. The test complex includes a flat mirror surface on which the control points with mutual arrangement were drawn. The focal length was determined by the measured coordinates of the points on the lens surface of the digital camera. But in this method, a precision mirror on a metal basis is used, and it is also necessary to select a control-measuring grid with hole for the various camera lenses. It is making the implementation of the method labor-intensive, reduces its cost and manufacturability. In publication [12] the authors analyzed the methods for determining the focal length in digital cameras and proposed a method, according to which the control-measuring grid (CMG) is located vertically at a distance from the DC and a photograph of the CMG is made, then the latter the CMG is moved along the optical axis of the digital camera to the distance, which is fixed with a micrometer screw and, repeatedly, a series of photographs of the CMG is taken. After that, on the received digital images, the coordinates are measured on the corresponding intersections of the CMG, and subsequently, the focal length for the DC is determined. For approbation of the method, the focal length in the following cameras was determined: Canon EOS 350D, Canon EOS 450D, Canon EOS 5D. The a priori estimation of accuracy of determining the focal length for the DC by the proposed method was calculated. It should be noted that today, the precision of the focal length determination is not
sufficient (for example, in paper the error of the focal lengths of the DC is - 0,02-0,05 mm, but acceptable requirements for today - 0,005-0,01 mm).

2. Materials and methods
The proposed method can be used for determining the focal length of non-metrical digital cameras in composing frontal planes of facades and interiors of architectural monuments, monitoring of deformations of engineering structures, landslide and rural processes, mines, glaciers and unmanned aircraft application etc. Technological realization of the method for determining the focal length of the DC includes such steps (Figure 1). On a tripod fix control-measuring grid 1 and level it using the overhead level. On second tripod fix cart with a micrometer screw 4 in the immediate proximity of the first tripod. Next, the digital camera 3 is set, so that the main optical axis 2 is approximately perpendicular to the CMG. The DC is leveled by the overhead level. After setting the complex, it is taking a photo of the CMG from the point S1 - the center of projection of the optical system in the first position (Figure 2). DC is moved along the optical axis with a micrometer screw and repeatedly takes a photo of the CMG from point S2 - the center of projection of the optical system in the second position. As a result, the images of CMG are acquired (Figure 3).

![Figure 1. Schematic arrangement of devices and elements of a surveying](image1)

![Figure 2. Scheme of determining the focal length of the DC.](image2)

![Figure 3. Determining the focal length of the DC.](image3)
For further research the length of the segment L is determined by the CMG cells. The segment L is chosen between the intersections of the CMG, which are presented on both images. Next, the coordinates (x, z) are measuring at the corresponding intersections of the CMG on the acquired images and calculate the lengths of the segments l1 – at the initial position of the DC and l2 - after moving the DC at the distance S1S2 fixed by the micrometer:

\[ l_1 = \sqrt{\Delta x_1^2 + \Delta z_1^2} , \]  
\[ l_2 = \sqrt{\Delta x_2^2 + \Delta z_2^2} , \]  

where, \( \Delta x_1, \Delta z_1 \) – the difference of the coordinates of the intersections of the CMG, that presented on the images – the ends of the segment l1; \( \Delta x_2, \Delta z_2 \) – the difference of the coordinates of the intersections of the CMG, presented on the images – the ends of the segment l2.

For further calculations, it is assumed that displacement of DC S1S2 equal to d, the distance between the initial position of the DC and CMG – Y=S1O, and the difference between the lengths of the segments l1 and l2 – \( \Delta l \). Then, from Figure 2 it follows:

\[ \frac{\Delta l}{l_1} = \frac{d}{Y} , \]  
Also, using scale equation:
 \[ \frac{f}{Y} = \frac{l_1}{L} , \]  
From formulas (5) and (6) determine the distance to the CMG, respectively:

\[ Y = \frac{l_1 d}{\Delta l} , \]  
\[ Y = \frac{fL}{l_1} , \]  
Equating (7) to (8):

\[ \frac{l_1 d}{\Delta l} = \frac{fL}{l_1} , \]
Then the focal length of the DC:

\[ f = \frac{l_1^2d}{\Delta lL}, \]  

(10)

The priori estimation of accuracy of the determination of the focal length of the DC is defined by the formula:

\[ m_f = \sqrt{m_{l_1}^2 + m_d^2 + m_{\Delta l}^2 + m_L^2}, \]  

(11)

where, \( m_{l_1} \) – the mean square error (MSE) of measuring length of segment \( l_1 \) on the image:

\[ m_{l_1} = \sqrt{m_x^2 + m_z^2}, \]  

(12)

where, \( m_x, m_z \) – MSE of measuring the coordinates on the image, which is equal to 2.5 microns; \( m_d \) – MSE of displacement determination of the DC by a micrometer, which is 4 microns; \( m_{\Delta l} \) – MSE of determining the length of the segments difference:

\[ m_{\Delta l} = \sqrt{2m_{l_1}}, \]  

(13)

\( m_L \) – MSE of engraving the intersections of the CMG, which is 2 microns.

To select the optimal parameters for determining the focal length of the DC, it is taken the differential an equation. Then the MSE:

\[ m_f = \sqrt{\left(\frac{2ld}{\Delta lL}\right)^2m_{l_1}^2 + \left(\frac{l_1^2d}{\Delta l^2L}\right)^2m_d^2 + \left(\frac{l^2d}{\Delta lL^2}\right)^2m_{\Delta l}^2 + \left(\frac{l_1^2}{\Delta lL}\right)^2m_L^2}, \]  

(14)

3. Results and discussions

From the analysis of formula (12) follows, the measurement error affecting the determination of focal length can be divided into two groups. The first group of errors acts in inverse proportion to the difference in the lengths of the segments \( \Delta l \), and the second is inversely proportional to the square \( \Delta l \). The first group includes the errors of determining the length of the segment on the image \( m_l \) and on the CMG \( m_{l_1} \) and the error of measuring the length of the displacement of the CMG \( m_d \). The second – is the error of determining the length of the segments difference \( m_{\Delta l} \). In this case, the error \( m_{\Delta l} \) will have the greatest impact on the focal length determination than the rest of the errors. Therefore, in order to minimize \( m_{\Delta l} \), it is recommended to measure at the intersections of the CMG in the central part of the image, with the condition that the coordinate \( z = \text{const} \). Then, the error \( m_{\Delta l} \) will depend only on the accuracy of the measurement abscise \( x \). The focal lengths of the Canon EOS 450D digital camera No2280509198 were determined with an average focal length of 55 mm for approbation the method. Several series of images were acquired. The coordinates at the corresponding intersections of the CMG by acquired images were measured in the Digitalis software package, namely the Models app. Results and parameters of research are presented in Table 1. The corresponding definition of the focal length for this camera, which is determined by the trigonometric method, is 53.909 mm [13].

Based on the data, it is presents graphs of variation of focal length with varying parameters of research and their approximation by a polynomial (Figure 4-6). Also, according to Formula 12, the effect of each of the errors on the accuracy of determining the focal length is considered in order to eliminate them by selecting the optimal parameters of surveying (Figure 7-10). As we can see from the presented data, it is optimal to choose the length of segment on the CMG close to 140 mm. It should be noted that in this case the focal length is 53.903 which does not exceed the estimated accuracy.
### Table 1. Determining of the focal length of the DC.

| No | x, μm | L, mm | d, mm | f, mm | m, μm |
|----|-------|-------|-------|-------|-------|
| 1  | 1165,3| 20    | 40    | 53,996| 7,8   |
| 2  | 1389,2|       |       |       |       |
| 1' | 1070,6|       |       |       |       |
| 2' | 1242,2|       |       |       |       |
| 1  | 2439,9| 40    | 40    | 53,913| 7,8   |
| 2  | 2671,5|       |       |       |       |
| 1' | 2222,1|       |       |       |       |
| 2' | 2404,7|       |       |       |       |
| 1  | 3709  | 60    | 40    | 53,936| 7,8   |
| 2  | 3957,1|       |       |       |       |
| 1' | 3372,1|       |       |       |       |
| 2' | 3567,6|       |       |       |       |
| 1  | 4974,8| 80    | 40    | 53,966| 7,8   |
| 2  | 5250,9|       |       |       |       |
| 1' | 4517,7|       |       |       |       |
| 2' | 4739,2|       |       |       |       |
| 1  | 5606,8| 100   | 40    | 54,032| 7,8   |
| 2  | 5915,8|       |       |       |       |
| 1' | 5091,3|       |       |       |       |
| 2' | 6867,8|       |       |       |       |
| 1  | 6764,3| 140   | 40    | 53,903| 7,8   |
| 2  | 7066,8|       |       |       |       |
| 1' | 6948,6|       |       |       |       |
| 2' | 8274  |       |       |       |       |
| 1  | 10655 | 160   | 40    | 53,903| 7,8   |
| 2  | 9815,8|       |       |       |       |
| 1' | 9659,3|       |       |       |       |
| 2' | 8867,8|       |       |       |       |
Figure 4. Variation of focal length with varying length of segment on CMG (solid line) and approximation by a polynomial (dashed line).

Figure 5. Variation of focal length with varying differences of length segments on images (solid line) and approximation by a polynomial (dashed line).

Figure 6. Variation of differences of length segments on images with varying length of segment on CMG (solid line) and approximation by a polynomial (dashed line).
Figure 7. The effect of the error of determining the length of the segment on the image $m_l$ (red) on the accuracy of determining the focal length.

Figure 8. The effect of the error of determining the length of the segment on the CMG $m_d$ (red) on the accuracy of determining the focal length.

Figure 9. The effect of the error of measuring the length of the displacement of the CMG $m_L$ (red) on the accuracy of determining the focal length.
Figure 10. The effect of the error of determining the length of the segments difference $m_\Delta l$ (red) on the accuracy of determining the focal length.

4. Conclusions
After analyzing literary sources, about the determination of internal orientation elements and calibration parameters of digital non-metric cameras allowed to find out the main difficulties while solving similar problems. It is proposed and tested method of determining the focal length digital camera that allow quickly in laboratory conditions to determine the focal length with appropriate precision, which is not exceeding accuracy measurement of images coordinates on the digital photogrammetric stations. Implementation of the method does not require angles measurements and the use of appropriate equipment. That why, the realization cost of the proposed method is reduced.

In the future work, it is planned to research the method of determining the focal length of digital camera.

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