Calibration of digital non-metric cameras for measuring works

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Abstract. The technique of digital non-metric camera calibration with the purpose of obtaining reliable spatial information on an object by its photos is given in the article. The procedure for performing calibration and processing the received images is described. The methods to deal with the issue, to perform geometric interpretation and to estimate the accuracy of the results obtained are given. The degree of influence of calibration on the final data is investigated. It is found that the accuracy of measurements increases with decreasing pixel size of the camera. The results of the comparison of control measurements with their true values are given, confirming the possibility of effective use of the cameras to solve practical problems of collecting geospatial information on engineering facilities.

1. Introduction

Digital household non-metric cameras are now of great interest for various applications, including photogrammetry. Their advantages in solving photogrammetric tasks are relatively low cost, simplicity and efficiency of obtaining a digital image, small mass and compactness, as well as continuous improvement of technical characteristics. The use of these cameras is being increasingly introduced into the measurement work, despite the lack of regulatory documents supporting the use of such measurement means.

In general, the quality of the images obtained depends to a large extent on the characteristics of camera lenses having certain levels of aberrations (distortions). At the same time, distortion of a lens has the greatest impact on the geometric dimensions of the objects depicted in the photographs. When conducting photogrammetric processing of digital images, it is required to know elements of internal orientation and components of distortion, which can reach appreciable values in cameras not intended for measuring purposes. Since the passport data of non-metric cameras often do not contain such information, it becomes necessary to perform calibration.

The issues of camera calibration were paid attention during the course of photogrammetry development. Studies in this field were conducted by leading Russian and foreign scientists, such as Lobanov A.N., Dubinovsky V.B., Zhurkin I.G., Antipov I.T., Tyuflin Yu.S., Malavsky B.K., Guk A.P., Goncharov A.P., Pogorelov V.V., Chibunichev A.G., Mikhailov A.P., Ackermann F., Brown D., Grun A., Jacobsen K., Norton C. etc. As a result, numerous methods of partial and complete calibration of cameras were proposed, differing by a large amount of field and desk work. All at once, it is sufficient to perform a laboratory calibration for the purpose of performing the measurement work.

The method of laboratory calibration, suitable for practical use, must meet the following requirements: the relative simplicity of creating a test object and its compactness; the possibility of
complete calibration, that is, the definition of elements of internal orientation and distortion; the minimum amount of measurements from the images. However, in a number of cases, a partial calibration is sufficient, that is, determining only the distortion, for example, to examine the orthoscopic properties of a camera lens or to obtain a distortion field for correcting images of planar objects.

2. Methods

The various software allows processing photographs taken with non-metric cameras to create three-dimensional models and orthophotos of photographed objects. Both foreign (PhotoModeler, Autodesk Recap Pro, IMAGINE Photogrammetry, SOCET SET) and Russian (PHOTOMOD, Agisoft Photoscan) programs are bright examples.

The main task of the study is to refine the calibration parameters of the camera. These parameters include:

- \( f \), focal length (pixels);
- \( x_0, y_0 \), coordinates of the main point;
- \( \delta x_0, \delta y_0 \), distortion factor.

The laboratory method that meets these requirements to some extent is based on the close-up shooting of the test object and the measurement of the pixel coordinates of the points. The further processing of the measurement results is based on the collinearity equations:

\[
x - x_0 = -f \frac{a_1 \Delta X + b_1 \Delta Y + c_1 \Delta Z}{a_3 \Delta X + b_3 \Delta Y + c_3 \Delta Z}
\]

\[
y - y_0 = -f \frac{a_2 \Delta X + b_2 \Delta Y + c_2 \Delta Z}{a_3 \Delta X + b_3 \Delta Y + c_3 \Delta Z}
\]

where \( x \) and \( y \) are coordinates of the point in the snapshot system; \( x_0, y_0 \) and \( f \) are the elements of internal orientation: the coordinates of the main point and the focal length; \( a_i, b_i \) and \( c_i \) are the direction cosines of the function of the corner elements of the external orientation of the image \( \alpha, \omega \) and \( \kappa \); \( \Delta X = X_G - X_S \); \( \Delta Y = Y_G - Y_S \); \( \Delta Z = Z_G - Z_S \); \( X_G, Y_G, Z_G \) are the geodetic coordinates of a point in the test object system; \( X_S, Y_S \) and \( Z_S \) are the coordinates of the image projection centre in the test object system.

Equations (1) after reduction to linear form can be represented by the formula:

\[
x_0 - \frac{x}{f} \delta f - \left( f + \frac{x^2}{f} \right) \alpha - \frac{xy}{f} \omega + \frac{y^2}{f} \kappa - \frac{f}{\Delta Z} \delta X_S - \frac{x}{\Delta Z} \delta Z_S = x - \bar{x}
\]

\[
y_0 - \frac{xy}{f} \delta f - \left( f + \frac{y^2}{f} \right) \alpha + \left( f + \frac{x^2}{f} \right) \omega - \frac{f}{\Delta Z} \delta Y_S - \frac{y}{\Delta Z} \delta Z_S = y - \bar{y}
\]

where \( \delta f \) is the correction to the approximately accepted focal length; \( \delta X_S, \delta Y_S \) and \( \delta Z_S \) are the corrections to the approximately accepted coordinates of the projection centre; \( x, y \) are the coordinates of the point, calculated from (1) on the basis of approximately accepted unknowns. The initial values of \( x_0, y_0 \) and \( \alpha, \omega, \kappa \) can practically be assumed as equal to zero.

Elements of the external and internal orientation of the image are determined from the system of equations (2) compiled for points with known geodesic coordinates. The system is solved iteratively by the method of least squares. At each iteration with approximately given initial data according to (1), a model image is created under the condition of minimal discrepancies between the calculated and measured values of the plane coordinates of points, that is, an image that is as close as possible to the real one. After the last iteration, the elements of exterior orientation are determined and the distortion is calculated:
\[ \delta x_i = x_i - \bar{x}_i - x_0, \quad \delta y_i = y_i - \bar{y}_i - y_0. \] (3)

The authors suggest a technique for determining the correction parameters of digital images obtained by non-metric cameras using a test polygon. Its key stages are:

1. Measuring the coordinates of control points of the test polygon (special marks) with a tacheometer and photographing with a camera from several points.
2. Determination of the reduction elements of the rear nodal point of the camera relative to the initial point of the coordinate system of a ground laser scanner and coefficients of polynomials (for example, Ebner, Jakobson, Grun, Brown, etc.) describing systematic errors in the coordinates of the points of the images. Errors in the coordinates of the points of the image are due to the distortion of a lens and the inaccuracy of the manufacturing of the charge-coupled device camera matrix.
3. Elimination of systematic errors in the measured coordinates of the points of the last image by means of polynomials and performance of quality control of the calibration.

3. Results
An amateur digital Canon EOS 1100D camera was used for calibration. The sequence of calibration of the camera on the test polygon is the following:

1. calculation of the approximate focal length of the camera by the image;
2. shooting of the test object (Fig. 1);
3. processing of shooting results;
4. equalisation of measurement results;
5. evaluation of the accuracy of the results.

As a test object during the study, a stand covered by a large number of coordinated brands of different planes was prepared (Fig. 1).

![Figure 1. Calibration stand](image)

The stand is located in the geodesy laboratory of the Saint Petersburg Mining University. The coordinates of the marks were determined using an electronic Sokkia CX-103 tacheometer and measurements were conducted in full.

The calibration sand was further photographed taking into account the convergent case with 100% overlapping of stereopair images. As a result of the photographing, stereopairs were obtained from the photography bases, at different distances from the test polygon.

The shooting was done from a tripod using the self-timer to minimise the distortion in the picture caused by the image shift. Photographing was conducted with the light of lamps without flash.
In the next stage, processing of photos to clarify the parameters of the camera was performed using Agisoft Photoscan software. The resulting images were loaded into the program, after which the alignment procedure was performed (the position and orientation of the camera for each frame were determined, and a sparse point cloud was also built). The coordinates of 48 marks received with the help of a tacheometer were imported, and binding to all photographs was carried out.

The alignment of the images was repeated to clarify the position and parameters of the camera. After that, the errors of the position of the marks were analysed. During the experiment, the errors did not exceed 2 mm. In addition, the current calibration parameters of the used camera were described (Table 1).

**Table 1. Calibration of the Canon EOS 1100D camera**

| Parameter                              | Value                  |
|----------------------------------------|------------------------|
| Pixel size, μm                         | 5.3                    |
| Focal length, mm                       | 18 mm                  |
| Focal length, pixels                   | 3546.22                |
| Coordinates of the main point x₀, y₀, pixels | 41.91; -29.50         |
| Radial distortion coefficients         | k₁ = 0.16838; k₂ = 0.149583; k₃ = 0.00342092 |
| Tangential distortion coefficients     | p₁ = 0.0026; p₂ = 0.0003 |

The calculation result can be considered as a correct one if the error value of the weight unit does not exceed 1 mm, and the average deviation value at reference points does not exceed 2 mm in plan and height. In order to analyse the eliminated distortion field, the corresponding surfaces were constructed using the found random error coefficients. The maximum standard calibration of the calibration is 4.8 μm. Since this value is smaller than the pixel size, the calibration result is considered satisfactory.

The second stage of the study was checking the calibration quality when performing the measurement work. A part of the facade of the inner courtyard of the Saint Petersburg Mining University was photographed as an example (Fig. 2).

![Figure 2. Fragment of the facade of Saint Petersburg Mining University](image)

The object was chosen since its surface laser scanning was previously performed, followed by the creation of orthophotos and dimensional-fixation documentation (drawings of facades, parts and sections), that is, the material to compare with the data obtained with the use of cameras was available. Photographing was performed according to the following rules:

- **Flat Object** shooting scenario;
- high resolution of images;
- absence of non-textured, reflective and transparent objects;
- stability of the relative positioning of objects in the process of shooting;
- large overlapping of pictures when shooting from multiple angles;
- linking the future model to the local coordinate system.

At the office work stage, the processing of received images was carried out. An estimation of the photograph quality was done based on comparing the clarity parameter of a particular image with the corresponding parameter for other photographs in the set. The value of the parameter is calculated based on the sharpness level of the sharpest part of the image. A photograph is considered substandard if the quality factor is less than 0.5. The photos were aligned, the dense cloud of points was built, the model was formed and textured (Fig. 3).

![Figure 3. Fragment of the textured facade model](image)

Then the model was adopted to a local coordinate system in which surface laser scanning data were presented. Using the cloud of the points of the lidar survey, the coordinates of 6 characteristic points, later transferred to the Agisoft Photoscan program (Fig. 4), were determined.

![Figure 4. Linking the facade model to the points](image)

At the next step of the study, all of the above actions were performed with the same photographs and coordinates of characteristic points. No camera calibration correction parameters were used that allowed carrying out a comparative analysis of two models and a drawing compiled from the data of surface laser scanning with the help of orthoimage. An example of such comparison is shown in Figure 5.
a) door size according to the model without calibration
b) door size according to the model with calibration
c) door size according to the drawing

Figure 5. — Comparison of the geometric characteristics of the object according to photogrammetric processing data and surface laser scanning

As a result, it can be concluded that non-metric cameras are suitable as equipment for measurements, and the drawings obtained correlate well with the accuracy requirements presented in Table 2.

Table 2. Requirements for the accuracy of measurement drawings according to GOST R 56905-2016

| Drawing scale | Type of a drawing                        | Error limits, mm |
|---------------|------------------------------------------|------------------|
| 1:1-1:20      | Drawings of details, templates, trace drawings | 1-2              |
| 1:50          | Drawings of plans, sections, facades      | 2-5              |
| 1:100         | Drawings of plans, sections, facades      | 10-20            |
| 1:200         | Overview drawings of plans, sections, facades | 30-50           |
| 1:500         | Schemes                                   | 200-300          |

However, it is necessary to carry out preliminary calibration of the camera used.

4. Conclusion

Since the use of consumer-grade cameras is becoming more common in photogrammetric applications, there is a need for appropriate calibration procedures. It is not always possible to perform self-calibration in practical measurement projects at close distance. Therefore, instead of performing self-calibration simultaneously with the object drawing, it is frequently better to calibrate first a camera using the appropriate network in order to restore all the relevant parameters (and not just the focal length). At the present time, calibration can be the completely automatic procedure and experience shows that temporary changes in calibration parameters for consumer class cameras are generally insignificant, considering that they are used at low and medium levels of accuracy.

References

[1] Koeva V P., Petrova D V and Zhechev M N 2003 Capabilities of Non-Metric Cameras for Ground Photogrammetry Geoprofi 4 19-21
[2] GOST R 56905 2016 Conducting measurement and engineering-geodetic work on objects of
cultural heritage
[3] Lazareva N S 2011 Application of digital non-metric cameras and laser scanners to solution photogrammetry problems Earth Science 1 80-91
[4] Ackermann F and Schneider W 1986 High Precision Point Transfer by Digital Image Correlation Int. Archives of Photogrammetry 26(III) 18
[5] Jacobsen K and Gerkeb M 2016 Sub-camera calibration of a penta-camera Int. Archives of Photogrammetry XL-3/W4
[6] Matsuoka R 2003 Proc. 6th Conf. on Optical 3D Measurement Techniques (Zurich, Switzerland) 130–137.
[7] Komissarov D V 2006 Method of calibration of digital non-metric cameras for ground laser scanners Geoprofi 6 32-34
[8] Nikitin V N 2014 Calibration of cameras from images of a flat test object Proceedings of high schools. Geodesy and aerial photography 2 71-80