Geometric calibration of a digital camera with a long-focus lens using a series of images with a common center of projection in the ProjNet software package

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Abstract

The article is a continuation of the research of the method of calibration of digital cameras equipped with a long-focus lens, using a series of images with a common projection center. When calibrating cameras with a long-focus lens on standard test objects, the calibration parameters are determined with low accuracy, and in some cases, calibration is impossible. To solve the problem of calibrating digital cameras with long-focus lenses, we propose a different approach that allows calibration on standard spatial test objects. The camera is mounted on a tripod with a panoramic head used by photographers to obtain spherical panoramas. The main condition for panoramic photography is that the center of rotation of the camera and the center of projection of the lens's optical system must be at the same point.
The article provides detailed information about the specialized software package ProjNet, specially developed for this calibration method and allowing you to calibrate digital cameras using images with a common projection center. The results of practical application of the calibration method are presented.
The article also presents a brief theory of central projection from the point of view of optics. The main misconceptions associated with the projection center and nodal points are described. The concepts of the entrance and exit pupils of the optical system, as well as their roles in the optical system of the lens, are considered.

1. Introduction

Long-focus lenses are lenses with a focal length 1.5 times or greater than the matrix size.
These lenses allow you to zoom in on the subject, but have a shallow depth of field and a small field of view.
For this reason, when shooting standard calibration test objects, a small number of points are captured in the image, the intersection angle is sharp, and the calibration parameters are determined with low accuracy, and in some cases calibration is impossible. For this reason, long-focus lenses are unpopular in photogrammetry. Even manufacturers of specialized long-focus cameras for photogrammetry supply them without calibration parameters.
The problem of calibration of long focal length camera is discussed in the photogrammetric literature (Cramer, 2004), (Cramer
et al, 2017), (Ergun, 2010), (Knyaz, 2015), (Fryer, 1996), (Remondino and Fraser, 2006), (Shortis, 2012). (Stamatopoulos, 2010), (Stamatopoulos, 2011) consider that two prospective approaches are available. The first is to investigate means to better accommodate numerical ill-conditioning, and the second is to look to the formulation of the functional model.
At the same time, there are situations when long-focus lenses can be useful, for example, when high detail of the pictures is required or the subject is at a distance and there is no way to get closer to it.
To solve the problem of calibrating digital cameras with long-focus lenses, we propose using the panoramic shooting method used to create 360-degree panoramas.
With this shooting method, the camera is mounted on a special panoramic tripod and the camera rotates around the projection center of the optical system. Observing this condition, all pictures will have a common projection center and this condition can be used during calibration as an additional geometric parameter.
Initially, this method was tested on mock-up pictures. The results of the first experiments are presented in the previous article by the authors (Chibunichev, Govorov, Chernyshev, 2019). These experiments showed that when using the calibration method with a common projection center, the accuracy of determining the elements of interior orientation increases. Most of all, this method has an effect on the accuracy of determining the focal length. In subsequent work, we focused on refining the theory and practical experiments with real cameras.

2. Methodology

2.1 Software

The method for calibrating long-focus cameras with a common projection center is based on the classic correction equation with one change, in calculations, not individual image projection centers are taken into account, but the overall one. It is important to note that the common projection center is a calculated value, not an average value for all images. The correction equation for three images with a common projection center is:

$$\begin{gathered} b_1\delta X_S + b_2\delta Y_S + b_3\delta Z_S + b_4\delta\omega_1 + b_5\delta\alpha_1 + b_6\delta\aleph_1 + \\ +b_7\delta\omega_2 + b_8\delta\alpha_2 + b_9\delta\aleph_2 + b_{10}\delta\omega_3 + b_{11}\delta\alpha_3 + \\ b_{12}\delta\aleph_3 + l_y = V_y; \\ b_1\delta X_S + b_2\delta Y_S + b_3\delta Z_S + b_4\delta\omega_1 + b_5\delta\alpha_1 + b_6\delta\aleph_1 + \\ +b_7\delta\omega_2 + b_8\delta\alpha_2 + b_9\delta\aleph_2 + b_{10}\delta\omega_3 + b_{11}\delta\alpha_3 + \\ b_{12}\delta\aleph_3 + l_y = V_y; \end{gathered} \tag{1}$$

where $\alpha_1, \alpha_2 ... \alpha_{12}, b_1, b_2 ... b_{12}$ – partial derivatives of the original equations with respect to unknowns (coefficients of the correction equation); X_s, Y_s, Z_s – coordinates of the projection center; $\omega, \alpha, \aleph$ – corner elements of external orientation; δ – corrections to the elements of the external orientation of the photograph; l_x, l_y – free members.

Unfortunately, most photogrammetric image processing programs do not allow changing the calculation formulas embedded in them. The use of mathematical programs such as

MATLAB is not always convenient when it comes to processing real images.

Especially for scientific purposes, at the Department of Photogrammetry of MIIGAiK, PhD Govorov A.V. developed the ProjNet program (Figure 1).

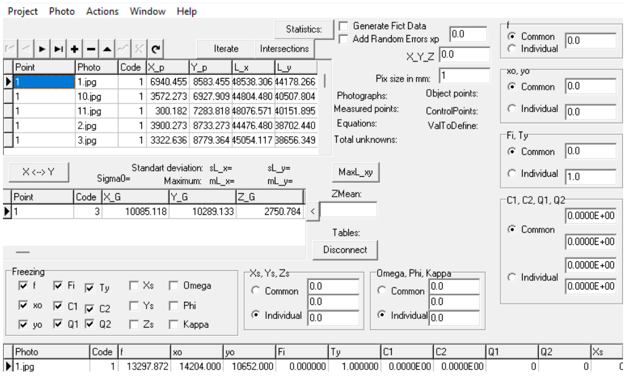

Figure 1. ProjNet program interface

This program allows flexible adjustment of the parameters of the defined elements. It is possible to fix individual orientation elements and make adjustments without taking into account certain parameters (Figure 2).

Figure 2. Setting options

It is possible to introduce random errors into measurements; this mechanism was used when working with model images (Figure 3).

Figure 3. Introducing random errors into measurements

A function for switching between individual and general calibration parameters was added specifically for the calibration method under study (Figure 4).

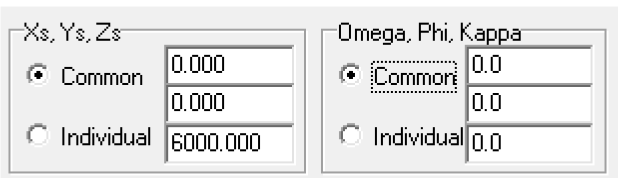

Figure 4. Switch between individual and common parameters

2.2 About the projection center

For our method, a mandatory condition is the rotation of the camera around the projection center of the optical system.

There are still disputes about what is the projection center of the lens's optical system?

In translations on photogrammetry and panoramic photography, it is often written that the projection center is one of the nodal points of the lens (Figure 5).

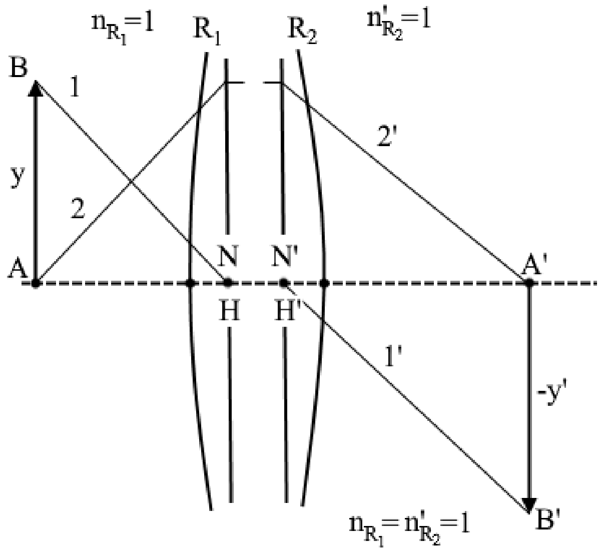

Figure 5. The front and rear nodal points N, N' in air ($n_{R_1} = n_{R_2} = 1$).

Nodal points are two conjugate points of the optical system.
Ray 1 from the off-axis point B of object AB, directed to the front nodal point N, exits through the rear nodal point N' of the optical system defined by surfaces R_1 and R_2, at the same angle as the incident ray, $a_N = a'_N$. For a system located in the air ($n_{R_1} = n_{R_2} = 1$) nodal points N, N' coincide with the principal points H, H' and the angular magnification $\gamma = a'_{N'}/a_N$ in these planes is equal to unity (Sveshnikova, Zapryagaeva, Guzeeva, Filonov, 2009). The front nodal point is in the object space, the rear one is in the image space. The distance from the rear nodal point to the plane of the photodetector is equal to the focal length of the lens (Chibunichev, 2022).
From this diagram it is logical to assume that the projection center is the front nodal point. But in practice this is absolutely not the case.
For example, the Canon EF-S 18-135mm f/3.5-5.6 IS USM lens has a point corresponding to the center of the optical system projection located behind the matrix plane. From the definition of nodal points, it follows that this cannot be a rear nodal point, since it must be located at a distance from the matrix equal to the focal length. It also cannot be a front nodal point, since in this case it will be located behind the rear one. Looking at the diagram of a simple optical system, we forget that the lens is a multi-component optical system, each lens of which has its own nodal points, and there are nodal points of the optical system itself. Also, one of the most important components is present in the optical system of the lens - the aperture diaphragm, which limits the beams of rays passing through the optical system of the lens. Such concepts as the entrance and exit pupil are associated with the aperture diaphragm (Figure 6).

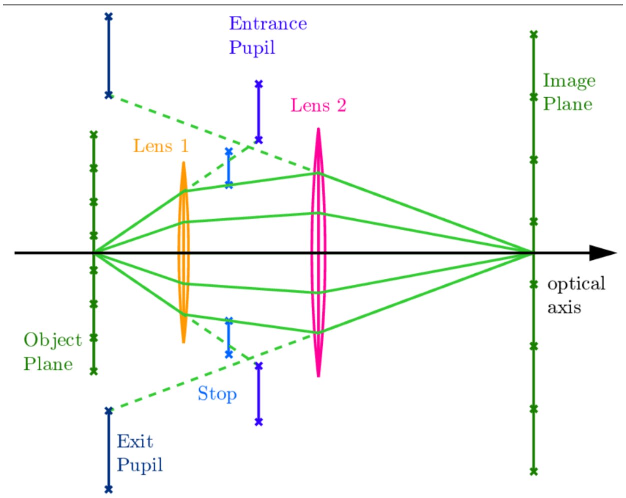

Figure 6. Entrance and exit pupils of the optical system

The entrance pupil is a paraxial (ideal) image of the aperture diaphragm through the lenses in front. The exit pupil is a paraxial (ideal) image of the aperture diaphragm through the lenses behind it (Mozharov, 2006). The entrance and exit pupils are conjugate. The rays that initially point to the entrance pupil of the objective pass through the aperture diaphragm. According to the monograph by D.V. Volosov, the projection center of the objective optical system is the center of the entrance pupil. If an additional diaphragm is installed in the optical system in front of the optical system, it will automatically become the entrance pupil; if an additional diaphragm is installed behind the optical system, it will automatically become the exit pupil (Volosov, 1978). This is exactly what can be seen in (Figure 5), where only the main points of the optical system are indicated, but some important elements are omitted for simplicity. This scheme of ray passage through a thin component will work only if there is an aperture diaphragm. In this case, the aperture diaphragm is the frame and in this case the entrance pupil is located in front and the exit pupil is behind the single component. The theory that the center of the lens projection is the center of the entrance pupil can be tested in practice using an external diaphragm and a panoramic shooting technique. A special panoramic head is used to rotate the camera around the projection center (Figure 7).

Figure 7. Panoramic head

In order to find the rotation point that coincides with the lens projection center, you need to select two objects located on the same line and shoot these objects at different camera rotations. In this case, you need to move the camera in the tripod to find the point around which, when rotating, the selected objects will not change their position relative to each other (Figure 8).

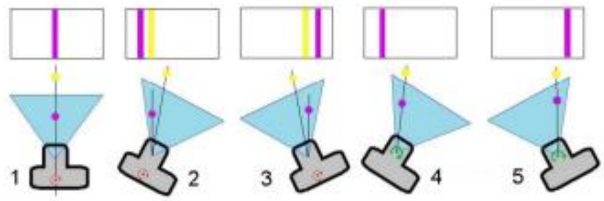

Figure 8. A practical method for finding the center of projection used in panoramic photography

The outer diaphragm was made from a lens cap (Figure 9).

Figure 9. Homemade external diaphragm

The objects of photography are a window frame in the background of the frame and a vertical bar in the foreground. According to the theory, the diaphragm installed in front of the optical system is the entrance pupil, and the center of the entrance pupil is the center of the projection of the digital photo camera. Therefore, when the camera rotates around a point passing through the center of the outer diaphragm, the selected objects of photography will not change their positions relative to each other. The shooting results are shown in Figure 10.

Figure 10. Shooting result. Camera rotation left, center and right

As can be seen in the pictures, the objects do not change their position when rotating around the center of the outer diaphragm (the center of the entrance pupil), therefore, the camera rotates around the center of the projection. This is consistent with the theory that the center of projection of a camera lens is the entrance pupil.

2.3 Refinement of the methodology for finding the projection center

According to the theory of pupils of the optical system, if we look into the lens through the front lens, we see an image of the diaphragm, constructed by the elements of the optical system in front of the diaphragm. The position of this image corresponds to the position of the entrance pupil of the lens. Based on this theory, the authors of the article proposed a new method for finding the rotation point of the camera in a panoramic head, which significantly simplifies the search method used in panoramic shooting.
If you take an electronic laser ruler (Figure 11) and point the measuring beam at the image of the diaphragm, when passing through the optical system, the beam will refract, and we will get an approximate distance to the position of the entrance pupil.

Figure 11. Electronic laser tape measure

The position is then refined using the projection center search method used in panoramic photography. This method of finding the projection center was used in the practical application of the calibration method.

3. Results and Discussion

To calibrate cameras at MIIGAiK, a marked spatial test object is used (Figure 12).

Figure 12. Marked spatial calibration test object at the Department of Photogrammetry MIIGAiK

Calibration of cameras with long-focus lenses using classical methods is practically impossible on this test object.

Calibration was performed on 4 cameras with different sets of lenses (Table 1).

Digital camera	Factory data	Objectives
Canon 70D	xo: 2736pix; yo: 1824pix; Pixel size: 0.0041mm	Canon 100mm Canon 135mm
Nikon DF	xo: 2464pix; yo: 1640pix; Pixel size: 0.0073mm	Pentacon Auto 135mm Kaleinar-5N 100mm
Hasselblad H4D-60	xo: 3354pix; yo: 4478pix; Pixel size: 0.0060mm	Hasselblad HC 100mm
PhaseOne iXM-RS100F	xo: 7102pix; yo: 5326pix; Pixel size: 0.00376mm	PhaseOne 50mm

Table 1. Cameras and lenses used

3.1 Результаты калибровки

3.3.1 Canon 70D

The calibration results are presented in Table 2.

Parameters	Canon 100mm	Canon 135mm
Sigma0	0,566068	0,662416
Focal length, pix (mm)	24395,5 +/– 2,0 (100,022)	33171,0 +/– 2,6 (136,001)
xo, pix	2697,8 +/– 5,6	2699,8 +/– 7,0
yo, pix	1823,3 +/– 7,8	1811,1 +/– 10,5
C1	$1,2537e^{-10}$ +/– $2,985925e^{-11}$	$3,2879e^{-10}$ +/– $2,178858e^{-11}$
C2	$-6,0233e^{-18}$ +/– $2,792432e^{-18}$	$-4,6446e^{-18}$ +/– $1,825534e^{-18}$
Number of photos	48	115

Table 2. Calibration results for Nikon DF with Canon 100mm and Canon 135mm lenses

3.3.2 Nikon DF

The calibration results are presented in Table 3.

Parameters	Pentacon Auto 135mm	Kaleinar-5N 100mm
Sigma0	0,523478	0,343744
Focal length, pix (mm)	18848,7 +/– 1,4 (137,596)	13740,6 +/– 0,6 (100,307)
xo, pix	2418,8 +/– 2,5	2474,9 +/– 1,0
yo, pix	1639,4 +/– 3,3	1668,8 +/– 1,4
C1	$1,8717e^{-09}$ +/– $2,730492e^{-11}$	$2,0250e^{-09}$ +/– $1,583858e^{-11}$
C2	$–5,8095e^{-18}$ +/– $3,064700e^{-18}$	$–1,1394e^{-16}$ +/– $1,801805e^{-18}$
Number of photos	80	58

Table 3. Calibration results of Nikon DF camera with Pentacon Auto 135mm and Kaleinar-5N 100mm lenses

3.3.3 Hasselblad H4D-60

The matrix size of this camera is 40.2×53.7 mm, and when using the Hasselblad HC 100mm lens, it falls into the category of medium-focus and can be calibrated using the standard method with individual projection centers. This camera is often used for aerial photography, it was decided to calibrate using the standard method with individual projection centers and the method with a common projection center and compare the results (Table 4).

Parameters	Calibration method	
	Individual projection centers	Common projection center
Focal length, pix (mm)	16663,8 +/– 2,3 (98,316)	16656,4 +/– 1,4 (98,272)
xo, pix	3363,2 +/– 2,3	3360,7 +/– 2,4
yo, pix	4522,7 +/– 2,5	4532,3 +/– 1,9
C1	$–1,8614e^{-10}$ +/– $9,878049e^{-12}$	$–2,0206e^{-10}$ +/– $9,939447e^{-12}$
C2	$–1,1706e^{-18}$ +/– $3,241053e^{-19}$	$–7,8066e^{-19}$ +/– $3,348799e^{-19}$
Number of photos	4	4

Table 4. Calibration results for the Hasselblad H4D-60 camera using the standard and common projection center methods

Next, the stereo pair of images obtained by this camera was processed using the obtained calibration parameters and an assessment of the accuracy of the obtained measurements was carried out (Table 5).

Coordinates	RMS, mm	
	Individual projection centers	Common projection center
X	0,173	0,161
Y	0,216	0,114
Z	0,495	0,310

Table 5. RMS of a stereo pair of images using the obtained calibration parameters

As can be seen from the obtained results, the accuracy along the Z axis increased by 1.5 times.

3.3.4 PhaseOne iXM-RS150F

Professional camera for aerial photography. The matrix size is 40.1x53.4mm. The camera has a medium focal length and can be calibrated using the classic method. As in the previous case, calibration was carried out using two methods (Table 6).

Parameters	Calibration method	
	Individual projection centers	Common projection center
Sigma0	0,515244	0,619825
Focal length, pix (mm)	13 736,4 +/–0,40 (51,649)	13 735,0 +/–0,4 (51,644)
xo, pix	7101,4 +/– 0,2	7101,1 +/– 0,3
yo, pix	5355,1 +/– 0,4	5356,2 +/– 0,4
C1	$–2,0369e^{-10}$ +/– $9,673891e^{-13}$	$–2,0373e^{-10}$ +/–$1,133164e^{-12}$
C2	$7,6815e^{-19}$ +/– $1,278454e^{-20}$	$7,6261e^{-19}$ +/–$1,487752e^{-20}$
Number of photos	6	6

Table 6. Calibration results for the PhaseOne iXM-RS150F camera using the standard and common projection center methods

As can be seen from the results, the use of the calibration method with a common projection center does not provide an advantage and, in this case, is inappropriate.

As part of practical experiments, there were attempts to calibrate a digital camera with Canon USM lenses. These lenses are equipped with an electronic image stabilization system. Such stabilizers, even when turned off, can affect the calibration parameters, for example, the coordinates of the main point. For this reason, lenses with electronic stabilizers should be avoided in photogrammetry.

4. Conclusion

The calibration method with a common projection center allows one to calibrate digital cameras with long-focus lenses on standard marked test objects. When rotating the camera, it is necessary to cover the entire surface of the matrix with marked points, rather than trying to catch as many points as possible in one frame. This allows you to most accurately describe geometric distortions during joint processing of images. Lenses with an electronic stabilization system are not recommended for use in photogrammetry, since they can have a significant impact on the coordinates of the main point. Using the common projection center calibration method when calibrating digital cameras with medium focal length lenses is not always advisable.

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