Testing the accuracy of different calibration methods

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Abstract

For many years, close-range photogrammetry has been dealing with the extraction of high accurate informations from images. The used techniques, mostly require a very precise calibration of cameras, either metric or non-metric cameras. This article presents the importance of a good determination of the intrinsic parameters in obtaining a high quality and accurate 3D model. In order to obtain the results, the 3D model of a sphere was created, using images acquired with the Canon PowerShot SX120 IS digital camera, whose intrinsic parameters were determined, using different calibration methods and objects. Finally, the 3D models obtained by using the same digital camera and different intrinsic parameters were compared with the model created with a precision of 10 µm based on the measurements made with the help of a micrometer. The differences between this models represent the influence of each calibration method on the accuracy of the final 3D model.

Keywords

accuracy, calibration, CMM,,digital images, 3D model

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1. Introduction

In recent years non-metric digital cameras are used to obtain metric information from our environment, due to the technological developments of this cameras, in areas such as accident reconstruction, industrial inspection and some heritage recording projects, but also metric cameras are still of great use in areas such as architecture [Remondino and Fraser, 2006].

In order to achieve accurate information of the three-dimensional (3D) world, the camera calibration process is an important task. The purpose of camera calibration is to describe the projection model that relates both coordinate systems, and to identify the intrinsic camera parameters so it can be used as a measurement device. Such parameters are usually calculated from a calibration target that contains easily and accurately detectable features in the captured image [Zhang, 2002].

There are many algorithm for this process that have been developed by several authors, such as: Duane C. Brown (1971) and Faig W. (1976) in photogrammetry community and more recently in computer vision by Gennery D. (1979), Ganapathy S. (1984), Olivier Faugeras and Giorgio Toscani (1986), Tsai (1987), Heikkilä and Silven (1997), Heikkilä (2000), Bakstein and Halir (2000), Zhang (2000).

Overview of calibration methods and some software for digital camera calibration are presented in [Remondino F. And Fraser C., 2006] and also in Gruen and Huang (2001), Fryer (1996), Klette *et al.* (1996), Godding (1999), Maas (1988), Kupfer and Wester-Ebbinghaus (1985), Wester-Ebbinghaus (1983), Brown (1971) as described in [Luhmann T. *et al*., 2006].

Three calibration methods can effectively be distinguished. These are characterised by the reference object used and by the time and location of calibration [Luhmann T. *et al*., 2006]: laboratory calibration, test field calibration and self-calibration.

The test field calibration methods can be classify into three categories [Zhang, 2004]:
- 3D reference object based calibration;
- 2D plane based calibration;
- 1D line based calibration.

This paper presents four test-field calibration methods to determine the parameters of a Canon PowerShot SX120 IS digital non-metric camera using one 3D calibration object and three 2D calibration objects and also the self-calibration method.

Calibration using 3D calibration objects yields very efficient results, although the calibration elements must be accurate and require an elaborate configuration [Zhang, 2000].

A non-metric camera is a camera whose interior orientation is completely or partially unknown and frequently unstable. All "off the shelf" or "amateur" cameras belong to this category are perhaps rather easily classified by the lack of fiducial marks [Faig, 1976].

The motivation of this paper is to determine which calibration object to be used in order to calibrate a non-metric camera, depending on the precision to obtain when reconstructing an object in 3D.

2. Camera calibration

For this study, a Canon PowerShot SX120 IS digital camera (10 Mega pixel), equipped with a 5.744 mm by 4.308 mm image sensor was calibrated using test field and self-calibration methods. The digital image taken with this camera has a resolution of 2816 x 2112 pixels.

Test field calibration is based o a suitable targeted field of object points with known coordinates or distances. This test field is imaged from several camera stations ensuring good ray intersections or a single camera station, filling the image format. Test field can be mobile or stationary. In general the design of the test field should be representative of the volume of the actual object to be measured. The number and distribution of image points are of major importance for an accurate determination of distorsion parameters [Luhmann T. *et al.*, 2006].

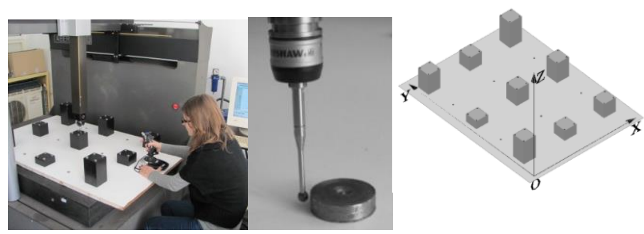
In the case of self-calibration, the test field is replaced by the object that needs to be reconstruct in 3D, so the intrinsic parameters are determined simultaneously with the object 3D model.

2.1 The Canon PowerShot SX120 IS digital camera calibration using 3D reference objects

For this case study a 3D reference objects was created.

It consists in a number of 42 points, 36 of them being placed in the corners of 9 wood cubes with different heights and 6 of them on a board. This object was then attached to a room wall in order to make image observations. Relative movements of targets on walls and so forth must be considered if the calibration range is to remain operative for a long period.

A coordinate measuring machine (CMM), produced by Aberlink, with an uncertainty within the working space of 2 µm, was used to place the target in the world coordinate system (Fig. 1 a,b). The 42 control points coordinates were measured in the (X, Y, Z) coordinate system, corresponding to the world coordinate system, with the XOY plane, the board plane and the OZ axis perpendicular to the board plane as it can be seen in Fig. 1c. For each control point were measured four points, the software automatically determining the best fit circle of the four points and then computing, all automatically the coordinates of the circle center and the circle diameter. The coordinates of the control points were registered automatically to a computer.



(a) (b) (c)

Fig. 1 (a), (b) Measuring the coordinates of the control points using a CMM and (c) the 3D reference object in the 3D world coordinate system

For the calibration process using this 3D object, the camera calibration toolbox for Matlab implementing the Heikkila & Silven's method was used. This Matlab toolbox is available at www.ee.oulu.fi/~jth/calibr/ and utilizes a new bias correction procedure for circular control points and a nonrecursive method for reversing the distortion model. Also, the technique developed by Heikkila and Silven (1997) first extracts initial estimates of the camera parameters using a closed-form solution (DLT-Direct linear transformation) and then a nonlinear least-squares estimation is applied to define the interior orientation and compute the distortion parameters. The model uses two coefficients for both radial and decentering distortion, and the method works with single or multiple images and with 2D or 3D calibration grids [Zhang Z., 2000].

In order to apply this calibration method the following elements have to be known: radius of control points r, the conversion factors Du and Dv, the 3D coordinates and the observed image coordinates of the control points.

The intrinsic parameters such as focal distance (f), optical center point (u_0,v_0), correction of radial distortion (k_1, k_2)

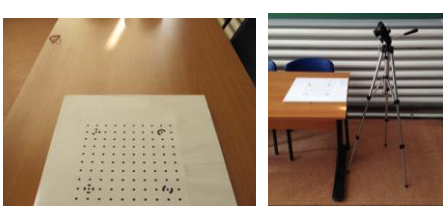
and correction of decentering distortion (p_1, p_2) for the three images taken with the Canon PowerShot SX120 IS digital camera as well as their average, are presented in Table 1.

Table 1. Physical Canon PowerShot SX120 IS digital camera parameters, calculated using Heikkila and Silven's method based on 3D calibration object

Image	***f [mm]***	***u_0 [pixels]/ v_0 [pixels]***	***k_1 [mm^{-3}]/ k_2 [mm^{-4}]***	***p_1 [mm^{-4}]/ p_2 [mm^{-4}]***
1	5.9898	1435.7557	8.971394	-5.882855
		1063.5828	-3.456568	-4.016074
2	5.9856	1432.6982	9.132086	-6.886404
		1067.9399	-3.538361	-4.421214
3	5.9932	1444.6962	9.165067	-6.170763
		1080.9282	-3.635191	-5.173718
Average	**5.9895**	**1437.7167**	**9.089516**	**-6.31334**
		1070.8170	**-3.543373**	**-4.537002**

2.2 The Canon PowerShot SX120 IS digital camera calibration using 2D calibration objects

The first 2D calibration field consist of a planar object point array, namely 100 points, distributed on 10 rows and 10 columns, printed on an A4 sheet. This planar sheet was placed on a flat surface that is a board with a uniform texture and color, as shown in Fig. 2, this shortening the time to determine the parameters of the camera used. The camera was placed on a tripod to ensure the camera and image stability.



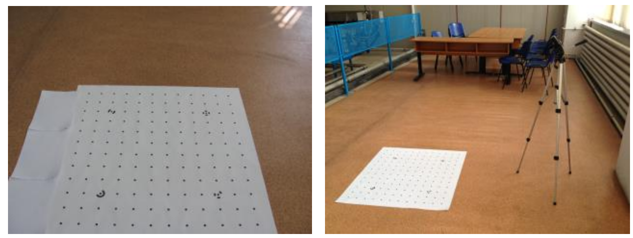
(a) (b)

Fig. 2 (a) 2D calibration object consisting in 100 points, (b) image acquisition for camera calibration

The images of the 2D calibration target, taken from the four sides of the planar target at various rotations, were processed using the *"PhotoModeler Scanner"* software, which automatically identified the points of the planar object point array (4 control points and 96 extra points) and calculated the calibration parameters of the camera using the "Camera Calibration Project ".

In the case of the calibration process, the average photo point coverage was 81%, the maximum error of marking the points was 0.711 pixels and the minimum error of 0.110 pixels (the overall residual was 0.125 pixels, the maximum RMS was 0.345 pixels, the minimum RMS was 0.058 pixels).

The second 2D calibration field consist of a planar object point array, namely 144 points, distributed on 12 rows and 12 columns, printed on an sheet of 36×36 inch (Fig. 3a). This planar sheet was placed on the floor. The camera was placed on a tripod to ensure the camera and image stability, as you can see in Fig. 3b.



(a) (b)

Fig. 3 (a) 2D calibration object consisting in 144 points, (b) image acquisition for camera calibration

The images of this 2D calibration target were taken and processed as in the previous case.

In the case of the calibration process, the average photo point coverage was 86%, the maximum error of marking the points was 0.875 pixels and the minimum error of 0.143 pixels (the overall residual was 0.185 pixels, the maximum RMS was 0.430 pixels, the minimum RMS was 0.094 pixels).

The intrinsic parameters calculated using the above described 2D calibration objects, are presented in Table 2.

Table 2. Physical Canon PowerShot SX120 IS digital camera parameters, calculated using 2D calibration objects fom Photomodeler library

2D calibration object	***f [mm]***	***u_0 [pixels]/ v_0 [pixels]***	***k_1 [mm^{-3}]/ k_2 [mm^{-4}]***	***p_1 [mm^{-5}]/ p_2 [mm^{-5}]***
100 control points	6.0660	1414.4263	6.431	-9.260
		1073.6082	-1.646	9.476
144 control points	6.0669	1410.3547	6.273	-9.181
		1067.9344	-1.807	2.894

The third 2D calibration field consists in pattern of both white and black squares, where one side contains an even number of squares, and the other contains an odd number of squares (asymmetric checkerboard), which can be found in the MatlabR2015 library, under the name "checkerboardPatter.pdf" (Fig. 4). The checkerboard pattern it is used because makes it easier to detect it automatically.

This pattern was printed and stick to a flat surface, namely a cardboard.

It is recommended to use 10 to 20 uncompressed images or images in lossless compression formats such as PNG for accurate calibration results, with no auto-focus and with constant zooming during images acquisition.

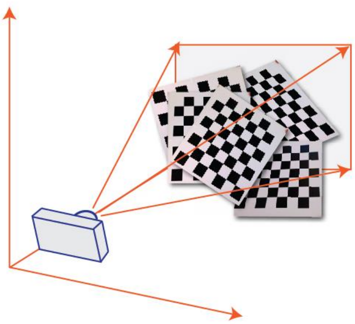


Fig. 4 2D calibration object consisting in an asymetric checkerboard

The calibration object must fulfill the entire image surface, it should be at approximately the same distance from the camera as the objects you want to measure and should be rotated so that the images to be taken from different angles using the digital camera to be calibrated.

The size of a square must be measured in world units, for example millimeters, as precisely as possible. In this example 18 images of the pattern were used with the square size of 61 mm and the camera calibration was done by the following steps:

a) Detecting the checkerboard corners in the images (Fig. 5).

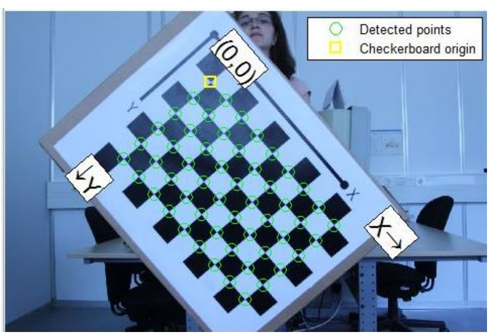


Fig. 5 Identifying automatically the squares corners

You can then check the accuracy of the checkboard detector by zooming in to inspect the results. In this way you can find bad detections and remove bad images.

(b) Generating the world coordinates of the checkerboard corners in the pattern-centric coordinate system, with the upper-left corner at (0,0). In this step a matrix which contains the squares corners coordinates is created.

(c) The process of camera calibration. In this step the intrinsic and extrinsic parameters are calculated as well as the radial and tangential coefficients (Table 3).

Table 3. Physical Canon PowerShot SX120 IS digital camera parameters, calculated using the checkerboard calibration pattern

***f* [mm]**	***u_0* [pixels]/ *v_0* [pixels]**	***k_1* [mm^{-4}]/ *k_2* [mm^{-4}]**	***p_1* [mm^{-6}] *p_2* [mm^{-6}]**
6.3898	1449.0977	-4.2373	2.9452
	1123.3805	2.7357	4.9445

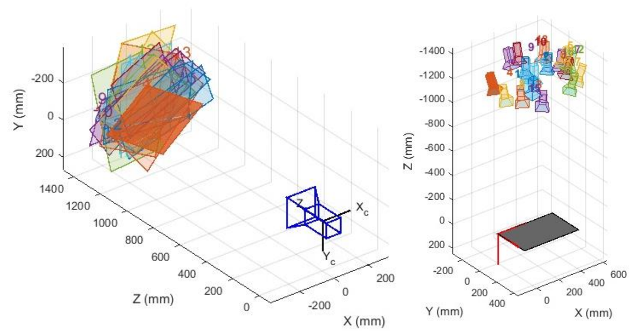
d) Evaluating the calibration accuracy. There are several ways to evaluate the accuracy of the estimated parameters:

-Plot the relative locations of the camera and the calibration pattern (Fig. 6 a,b);

-Calculate the reprojection errors (Fig. 7,8);

-Calculate the parameter estimation errors.

Reprojection errors provide a qualitative measure of accuracy. They were graphically represented as a bar graphic, each bar showing the mean reprojection error for the corresponding calibration image (Fig. 7), and also as a point cloud (Fig. 8). The reprojection errors are the distances expressed in pixels between the corner points detected in the image, and the corresponding ideal world points projected into the image. In the case of the graphic bar, in order for the calibration process to be accurate the reprojection errors must be smaller than 1 pixel.



(a) (b)

Fig. 6 Extrinsic parameters visualization (a) the relative positions of the calibration pattern in the camera's coordinate system, (b) the locations of the camera in the pattern's coordinate system

In the case of the point cloud, a good calibration, consists of a compact point cloud and the outermost point may indicate possible problems with the image of belonging. To improve accuracy the image may be removed.

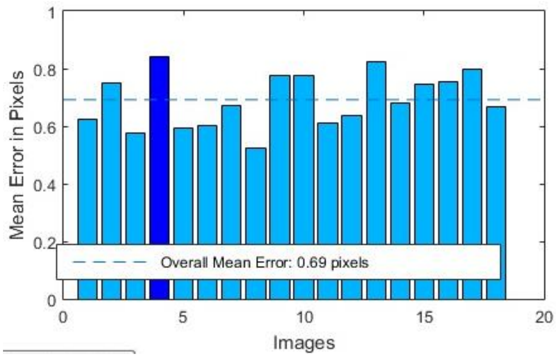


Fig. 7 Graphic bar representing the mean reprojection error per image

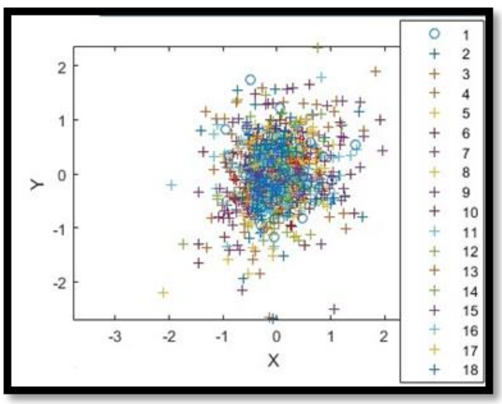


Fig. 8 Point cloud representing the mean reprojection error per image

Estimation errors represent the uncertainty of each estimated parameter, being calculated in the same units as the corresponding parameter (Table 4).

Table 4. Standard errors of estimated Canon PowerShot SX120 IS digital camera parameters

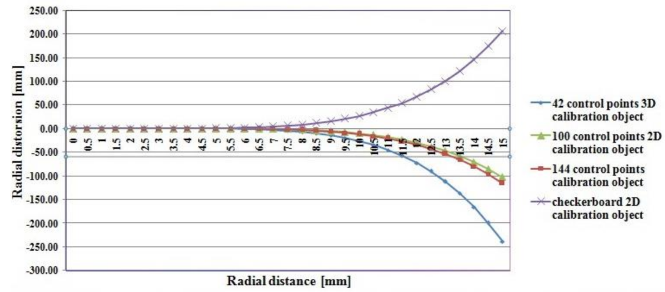
f [mm^{-2}]	***u_0 [pixels]/ v_0 [pixels]***	***k_1 [mm^{-5}]/ k_2 [mm^{-4}]***	***p_1 [mm^{-6}] p_2 [mm^{-6}]***
1.9117	4.8632	1.494825	6.329200
	4.7778	1.555967	5.061966

2.3 The Canon PowerShot SX120 IS digital camera calibration using self-calibration method

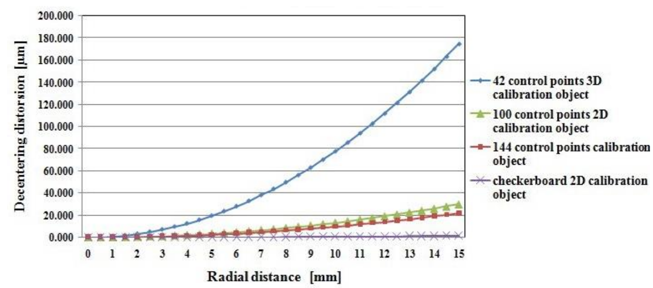
As we mentioned above, when using the self-calibration method, the intrinsic parameters are determined simultaneously with the object 3D model. So, this process is described in the next subsection.

2.4 The Canon PowerShot SX120 IS digital camera distorsion profiles

The radial and decentering distortion profiles for the Canon PowerShot SX120 IS digital camera, were computed using the values obtained by 4 different calibration objects (Fig. 9). To model the radial distortion Δr the odd-order polynomial $\Delta r = k_1 r^3 + k_2 r^5$ was used, where r is the radial distance. The decentering distortion $P(r)$ was graphically represented in a manner similar to the radial distorsion, using the function $P(r) = \sqrt{p_1^2 + p_2^2} \cdot r^2$.



(a)



(b)

Fig. 9. (a) Radial and (b) decentering distortion profiles for the Canon PowerShot SX120 IS digital camera, computed using the values obtained by 5 different calibration methods

3. 3D reconstruction of a sphere

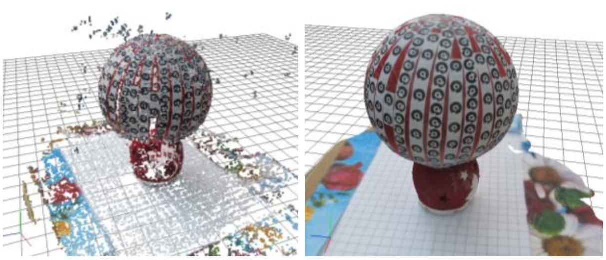
In order to determine which calibration object to be used for a digital camera calibration when we want to reconstruct an object in 3D (in these experiments a small size object), we chose a sphere whose 3D model was created based on the digital images taken with the Canon PowerShot SX120 IS digital camera whose interior orientation parameters were obtained by different calibration methods.

First, the sphere radius was measured with a precision of 10 µm using a micrometer obtaining a value of 69.175 mm. Then the sphere was placed on a 2D grid of squares and photographed all around being taken 18 images from 18 different camera positions distributed circularly around the object (Fig. 10).

Fig. 10 Image acquisition for the sphere 3D reconstruction

The images were processed automatically, using two different software.

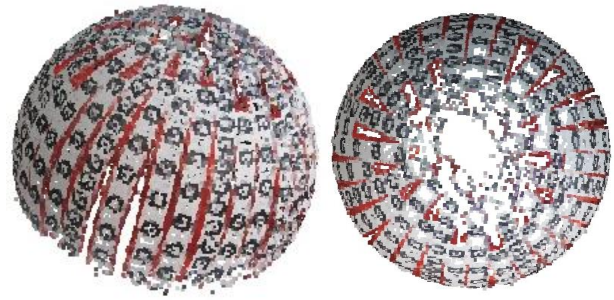
First a point cloud was automatically generated using the *"3DF Zephyr Pro"* software, containing a number of 34917 points (Fig 11). Using the local coordinates of three points, representing the grid intersections, the point cloud was brought in a local system with the XOY plane in the grid plane, the RMS (Root Mean Square) being 0.072 mm. Knowing that the 2D grid size is 10 mm, the point cloud was scaled using one control distance with a length of 19 squares, namely 190 mm, defined by two corners situated in the immediate vicinity of the sphere, which were clearly identified in the images, the scale factor being 154.12. In order to calculate the RMS, four distances representing the sides of a rectangle (three of his corners are the control points used to align the point cloud to the local coordinate system) were measured before and after the scale process, the RMS being 0.527 mm.



(a) (b)

Fig. 11. The sphere 3D model, created in the "*3DF Zephyr Pro*" software (a) point cloud, (b) mesh surface

The point cloud was imported into *„CloudCompare"* software where, through the filtering process, only the points corresponding to the sphere surface were extracted, namely 16805 points (Fig. 12).



(a) (b)

Fig. 12 Point cloud representing the sphere obtained after the filtering process (a) perspective view, (b) top view

In the second case, the RAD coded targets placed all over the sphere surface were marked automatically on each image individually and the corners of the same rectangle as in the previous case and some additionally grid intersections were manually marked using the *"Photomodeler Scanner software"* (Fig. 13). By processing the data, using the Bundle adjustment algorithm implemented into the "*Photomodeler Scanner software"*, the 3D coordinates of all referenced points were computed, their measurement precision was estimated and also the spatial locations and orientation angles of each camera were calculated. Thus, were computed the 3D coordinates of a number of 366 targets, of which a total of 52 points represents the 2D grid intersections (Fig. 13).

The points coordinates were brought in the same coordinate system as the automatically generated point cloud, using the same three control points. Then, the object was scaled using the same control distance as in the previous case, the RMS being 0.457 mm and the scale factor 154.13.

For this case study, all the image coordinates errors were less than 5 pixels tolerance suggested by *"PhotoModeler Scanner"*. The overall residual of the project was 0.719 pixels, less than the recommended of 5 pixels. The total error for determining the world coordinates, range between 0.011 mm and 0.587 mm. The angles between the projection rays range between $6^0.7488 \div 89^0.9956$, the recommended angle being of 90^0, with an average of $74^0.6181$.

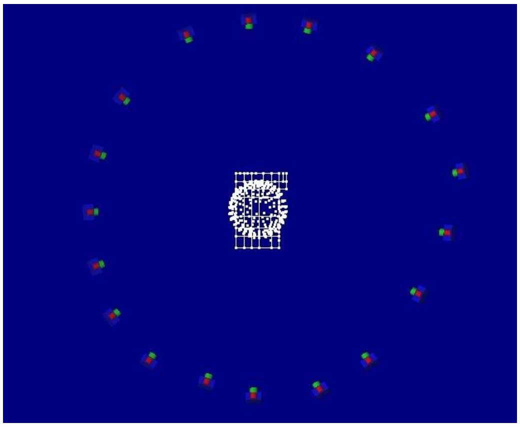


Fig. 13 A screen shot of the 3D Viewer with the final set of three-dimensional control points and cameras displayed

To approximate the mathematical shape of the object, namely with a sphere, the least-squares method was used. The starting point was the implicit equation of a sphere, with the form:

$$(x-a)^2+(y-b)^2+(z-c)^2-r^2=0 \quad (1)$$

where:
r- the sphere radius,
(a,b,c)-the sphere center coordinates.

The following function will be considered:

$$F_i=r_i^2-r^2=(x_i-a)^2+(y_i-b)^2+(z_i-c)^2-r^2 \quad (2)$$

The equation (2) can be used for initial values of the sphere center coordinates and the sphere radius calculation. The equation for a point P_i on the sphere circumference is:

$$F_i(a,b,c,r)=x_i^2+y_i^2+z_i^2-2ax_i-2by_i-2cz_i + (a^2+b^2+c^2-r^2)=0 \quad (3)$$

We note the term ($a^2+b^2+c-r^2$) with ρ and the equations system for *n* data points, written in matrix form is:

$$\begin{pmatrix} -2\cdot x_1 & -2\cdot y_1 & -2\cdot z_1 & 1 \\ -2\cdot x_2 & -2\cdot y_2 & -2\cdot z_2 & 1 \\ ... & ... & ... & ... \\ -2\cdot x_n & -2\cdot y_n & -2\cdot z_n & 1 \end{pmatrix} \cdot \begin{pmatrix} a_o \\ b_o \\ c_o \\ \rho_o \end{pmatrix} + \begin{pmatrix} x_1^2+y_1^2+z_1^2 \\ x_2^2+y_2^2+z_2^2 \\ ... \\ x_n^2+y_n^2+z_n^2 \end{pmatrix} = \begin{pmatrix} F_1 \\ F_2 \\ ... \\ F_n \end{pmatrix} \quad (4)$$

In order to solve this system by the least-squares method, $F_i=0$ is considered. The equations system (4) can be written in matrix form as: BX+L=0. The system solution is the *X* vector of the following form: $X=-(B^TB)^{-1}B^TL$.

Calculations were performed for the point cloud which was automatically generated using the "3DF Zephyr Pro" software and for the RAD coded targets automatically calculated using the *"Photomodeler Scanner software"* and different calibration parameters.

Next, we will refer to the RAD coded targets whose 3D coordinates were calculated using the digital camera intrinsic parameters obtained by using the 100 control points 2D calibration object.

The initial estimates for the sphere center coordinates and the sphere radius are:

$$a_o = 57.2620\,\text{mm};\ b_o = 98.3711\,\text{mm};$$
$$c_o = 126.4812\,\text{mm};\ r_o = 69.5514\,\text{mm}$$

The sphere that best fit the measured points is obtained by minimizing the distances (perpendiculars) drawn from each point to the sphere circumference. The Gauss Newton method is used to arrive at the final values for center coordinates and radius. The function is linearized by a Taylor series expansion around four provisional values (a_0, b_0, c_0, r_0) and the first order terms are detained:

$$G_i(a,b,c,r)=G_i(a_o,b_o,c_o,r_o)+\left(\frac{\partial G_i}{\partial a}\right)_o da+\left(\frac{\partial G_i}{\partial b}\right)_o db +\left(\frac{\partial G_i}{\partial c}\right)_o dc+\left(\frac{\partial G_i}{\partial r}\right)_o dr+...$$

(5)

where:

$G_i(a,b,c,r)=d_i=r_i-r$;

a_o, b_o, c_o and r_o – the provisional values of the unknowns obtains by solving the equations system (4);

$r_i=\sqrt{(x_i-a_o)^2+(y_i-b_o)^2+(z_i-c_o)^2}$ - the distances drawn from each point to the sphere center.

By conveniently grouping the terms, the unknown parameters of the sphere corrections equations system results, written in matrix form [Oniga E. and Chirila C., 2012]:

$$B_{r,4}X_{4,1}+L_{r,1}=V_{r,1},\quad with \quad P_{r,r} \quad (6)$$

where:

$$B_{r,4} = \begin{pmatrix} \frac{-(x_1-a_o)}{r_1} & \frac{-(y_1-b_o)}{r_1} & \frac{-(z_1-c_o)}{r_1} & -1 \\ \frac{-(x_2-a_o)}{r_2} & \frac{-(y_2-b_o)}{r_2} & \frac{-(z_2-c_o)}{r_2} & -1 \\ \dots & \dots & \dots & \dots \\ \frac{-(x_r-a_o)}{r_r} & \frac{-(y_r-b_o)}{r_r} & \frac{-(z_r-c_o)}{r_r} & -1 \end{pmatrix},$$

$$X_{4,1} = \begin{pmatrix} da \\ db \\ dc \\ dr \end{pmatrix}, \quad V_{r,1} = \begin{pmatrix} v_1 \\ v_2 \\ \dots \\ v_r \end{pmatrix},$$

$$L_{r,1} = \begin{pmatrix} \sqrt{(x_1-a_o)^2+(y_1-b_o)^2+(z_1-c_o)^2} - r_o \\ \dots\dots\dots \\ \sqrt{(x_r-a_o)^2+(y_r-b_o)^2+(z_r-c_o)^2} - r_o \end{pmatrix},$$

$$P_{r,r} = \begin{pmatrix} 1/s_{t_1}^2 & \dots & 0 \\ \dots & \dots & \dots \\ 0 & 0 & 1/s_{t_r}^2 \end{pmatrix}$$

The weights matrix has on its main diagonal the inverses of the squares of the spatial errors corresponding to the artificial control points and all the other elements equal to zero.

The normal equations system is:

$$N_{n,n} X_{n,1} + T_{n,1} = O_{n,1},$$

$$where \quad N = B^T PB \; and \; T = B^T PL \qquad (7)$$

from where the unknowns vector is:

$$X_{n,1} = -N_{n,n}^{-1} T_{n,1} = -Q_{n,n} \cdot T_{n,1} \; (Q = N^{-1})$$

The determination precision of the sphere radius from the unknown matrix is expressed with the mean square error:

$$s_r = s_o \sqrt{Q_{4,4}} = 0.067 \; \mu m,$$

$$where \quad s_o = \sqrt{\frac{[V^T PV]}{r-n}} = 0.068 \; mm, \; with \; r = 314 \; and \; n = 4 \qquad (8)$$

After solving the equations system, the compensated parameters of the sphere that best fits the 314 artificial control points are calculated:

$$a = 57.2719\,\text{mm}; \; b = 98.3711\,\text{mm};$$
$$c = 126.4806\,\text{mm}; \; r = 69.5463\,\text{mm}.$$

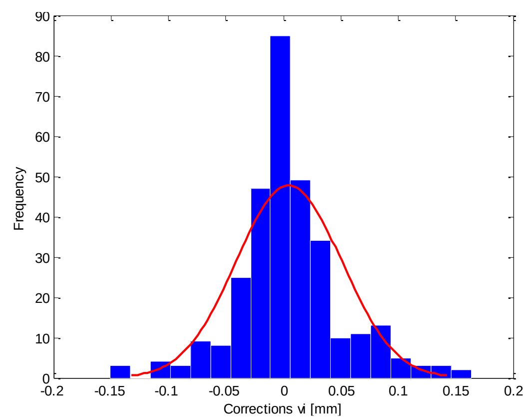
A threshold of 0.1 mm for the corrections values was imposed, so the points with the corresponding corrections greater than the threshold are eliminated after the first iteration, in this case 18 points.

The process is iterative until all unknowns do not change significantly. A routine in the MATLAB programming language was written. First a *.txt file was created containing a column with the detailed point number, three columns with the coordinates (X, Y, Z) in the local system defined in the "*Photomodeler Scanner software"* and three columns containing the measurement accuracies of the three coordinates.

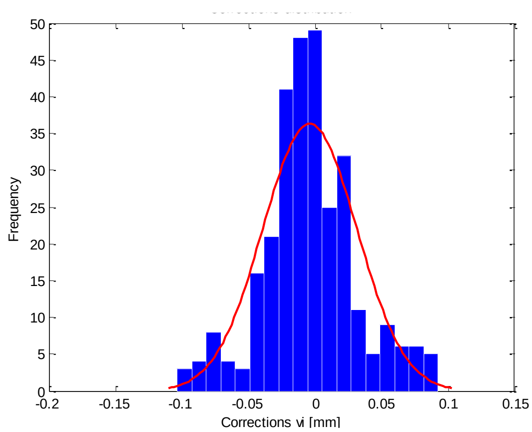
A total number of six iterations was effectuated, obtaining a maximum positive initial correction (after the first iteration) of 0.1632 mm, a maximum negative of -0.1506 mm and a minimum correction of 0.1 μm. The corrections histogram obtained after the first iteration is presented in Fig. 14a and the corrections histogram obtained after the sixth iteration in Fig. 14b.

The final values for the sphere center coordinates and the sphere radius, determined with a precision of 0.039 μm after six iterations, are:

$$a = 57.6423\,\text{mm}; \; b = 98.3268\,\text{mm};$$
$$c = 126.6113\,\text{mm}; \; r = 69.5536\,\text{mm}.$$



(a)



(b)

Fig. 14 The corrections distribution histogram obtained after (a) the first iteration, (b) the sixth iteration

The sphere that best fits the 296 artificial control points and the sphere represented by the initial parameters are shown in Fig. 15.
The spheres rays derived from measurements made on digital images using different intrinsic parameters and the differences between them and the one measured using a micrometer are listed in Table 5.

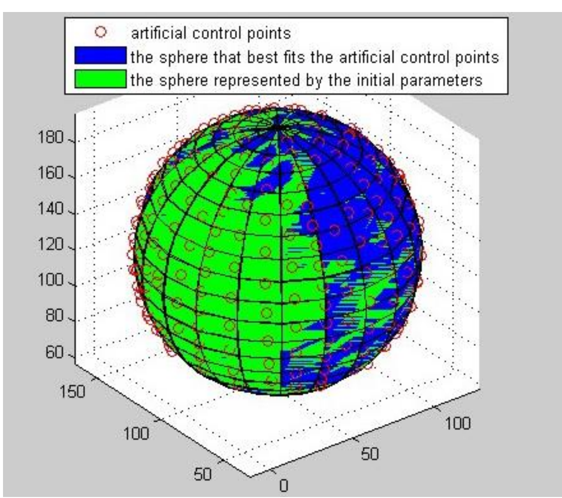


Fig. 15 The sphere that best fits the artificial control points and the sphere represented by the initial parameters

Table 5: The rays of the spheres that best fits the points measured on digital images using the parameters calculated with 2D and 3D calibration objects, as well as the residual errors

Calibration object	**Sphere radius**	**RMSE [mm]**	**RMSE [%]**
42 control points (3D)	69.0145	-0.1605	-0.23
100 control points (2D)	69.5536	0.3786	0.54
144 control points (2D)	69.6100	0.4350	0.62
Self-calibration	68.0032	-1.1718	-1.72
Checkerboard pattern (2D)	70.5424	1.3674	1.94

4. Conclusions

All lenses, whether of a metric, semi-metric or non-metric photogrammetric cameras, suffer from aberrations, that are known as radial and decentering distortion. Before any camera system is used for photogrammetric projects, the intrinsic parameters of the camera: focal length (f), optical center point (u_0,v_0), correction of radial distortion (k_1, k_2), correction of tangential distortion (p_1, p_2) and the medium image scale factor s_u, as well as the extrinsic parameters (r_{ij}, X_0, Y_0, Z_0) should be determined in the calibration process. A non-metric camera, the Canon PowerShot SX120 IS digital camera, was calibrated in this article using both 3D calibration objects and 2D calibration objects and also the self-calibration method.
The accuracy in 3D reconstruction of an object is directly proportional to the scale factor, so it is recommended to use a 2D grid to be photographed simultaneously with the object.
The best accuracy was obtained with the calibration parameters calculated based on the 42 control points 3D calibration target and the lowest accuracy was obtained with the calibration parameters calculated based on the checkerboard pattern. Using artificial control points placed all over the object surface, a much better measurement precision can be obtained than in the case of the natural control points. The minimum 3D reconstruction error of the sphere was 0.16 mm, representing 1:862 from the object dimension and the maximum 3D reconstruction error was 1.37 mm, representing 1:101 from the object dimension.
These experiments represent an analysis of the precision of object 3D reconstruction process when using a non-metric camera calibrated with different calibration objects and methods, because in areas such as camera based 3D measurements and robot vision, high geometrical accuracy is needed.

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