A COMPARATIVE STUDY ON CAMERA CALIBRATION ALGORITHMS

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Abstract: *In the recent decade, buildings 3D models are in a high demand by many public and private organizations. The extraction procedure of high accuracy measurements from images is one of the principal tasks of close-range photogrammetry. The particular techniques used in buildings 3D models creation mostly require an accurate calibration process of metric or non-metric digital cameras. Over the years, there were developed many calibration algorithms by several authors, such as: Tsai, Heikkilä & Silven, Bakstein & Halir, Zhang, etc. This paper aims to present a comparison between the intrinsic calibration parameters determined using the Tsai calibration algorithm, respectively the Heikkilä & Silven algorithm and their influence on building 3D model accuracy. In order to obtain the results, the 3D model of the historical monument "Dosoftei House" from Iaşi-City was created, based on image – data acquired with the Nikon Coolpix L810 digital camera. The camera calibration process, was performed using a 3D calibration object and the two algorithms mentioned above.*

Keywords: *building, 3D model, image, accuracy, calibration*

1. Introduction

Nowadays, there is a growing interest in the construction of 3D models, especially of urban and build environment, being used in many scientific domains of activity, such as: architecture and preservation, engineering, archaeology, surveying, medical and chemical industries, design projects, tourism, property sector and also the emergence situations institutes [1]. An important advantage of buildings 3D modelling is the capability of preservation in time of the city image. The buildings 3D models are useful for many applications such as: urban planning and environmental simulation, cartography, tourism and mobile navigation. Automatically generating buildings 3D models, in the form of 3D CAD representation, is the major part of city modelling and a challenge for many researchers.

In recent years, non-metric digital cameras have known a great technical development, being used in extracting metric information from the environment, in areas such as traffic collisions and accident reconstruction, industrial inspection, preservation and cultural heritage projects [2].

A non-metric digital camera is a camera with a completely or partially unknown interior orientation and often unstable. All "off the shelf" or "amateur" cameras are integrated in this category, being characterized by the absence of fiducial marks [3]. Thus, in order to obtain the optical characteristics of a non-metric digital camera, also called intrinsic parameters, a camera calibration process is required.

Camera calibration is a fundamental process, that has always been an essential component of photogrammetric measurement. The camera calibration process is used to obtain metric information of the three-dimensional (3D) world from two-dimensional (2D) images. Many applications such as close range three dimensional measurement and other two dimensional measurement tasks require a precise cameras calibration process. Thus, corrections of image distortion in cameras has been an important topic over time [4].

Camera calibration continues to be an area of active research within the CV community, with a perhaps unfortunate characteristic of much of the work being that it pays too little heed to previous findings from photogrammetry [5]. Over time, in photogrammetry and CV literature there have been reported various camera calibration algorithms. These algorithms are generally based on perspective or projective camera models and they are developed by several authors, such as: Tsai (Tsai, 1987), Heikkilä & Silven (Heikkilä & Silven, 1997), Bakstein & Halir (Bakstein & Halir, 2000) or Zhang (Zhang, 2000).

In this paper are presented the Tsai and also the Heikkilä and Silven's calibration algorithms to determine the intrinsic parameters of the non-metric digital camera Nikon L810. Tsai's calibration model assumes that some parameters are provided by the manufacturer, to reduce the initial guess of the estimation. It requires *n* features points ($n > 8$) per image and solves the calibration problem with a set of *n* linear equations based on the radial alignment constraint. A second order radial distortion model is used while no decentering distortion terms are considered. The two-step method can cope with either a single image or multiple images of a 3D or planar calibration grid, but grid point coordinates must be known [5].

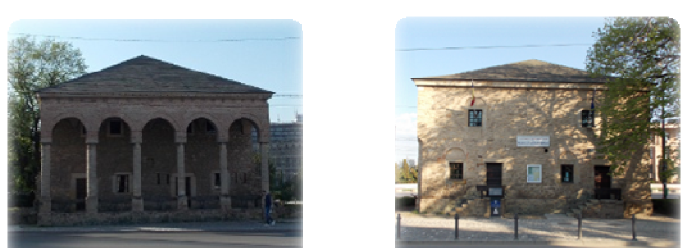
The technique developed by Heikkilä & Silven first extracts initial estimates of the camera parameters using a closed-form solution (DLT) and then a nonlinear least-squares estimation is applied to define the interior orientation and compute the distortion parameters. The model uses two coefficients for both radial and decentering distortion, and the method works with single or multiple images and with 2D or 3D calibration grids [6].

The principal purpose of this article is to find out the intrinsic parameters of a non-metric digital camera, using two different calibration algorithms, Tsai's and Heikkilä and Silven's calibration algorithm, in order to determine the degree of influence on a building 3D model accuracy, created based on digital images.

2. Presentation of the Study Area, Materials and Equipment

2.1. Presentation of the Study Area

Museum of Old Moldavian Literature from 1970, the "Dosoftei House" also known as "The House with Arcades", located in Iasi city (Romania), Anastasie Panu Avenue no.54, was the Metropolitan of Moldavia between 1670 and 1686. Built from stone, the historical monument has a special architecture with a regular cubic shape (Fig. 1).



(a) (b)

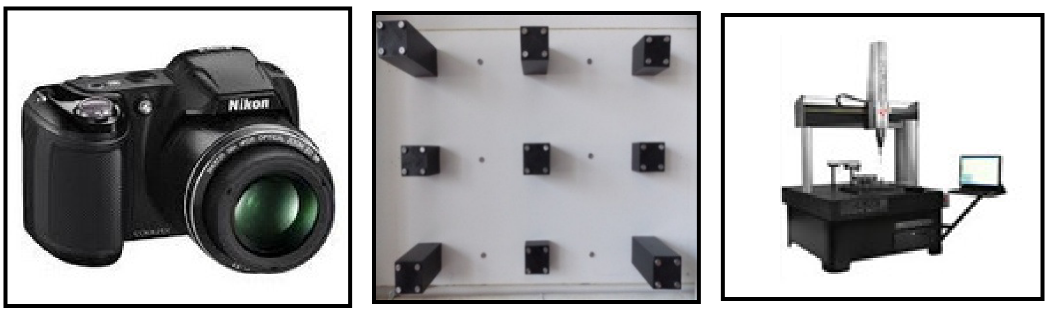
Fig. 1. The study building - "Dosoftei House" Museum (a) perspective view of the main facade and (b) perspective view of the main side facade

2.2. Materials and Equipment

The images of the historical monument were acquired with a Nikon Coolpix L810 digital photo bridge camera (16.1 Mega pixel), equipped with a 6,26 mm by 4,69 mm image sensor (Fig. 2a). In this paper, there were used digital images with the greatest resolution of 4608 x 3456 pixels and a 1,359 μm pixel size, taken with the minimum focal length.

The camera calibration process was performed by using a 3D calibration object. This target contains a number of 42 points, 36 placed in the corners of 9 wood cubes and 6 placed at the middle of the distance between them, with different heights. These 42 control points have 18 mm in diameter and consist of metal parts manufactured by means of a lathe (Fig. 2b). This target was attached to a room wall [6].

In order to place the 3D calibration grid target in the world coordinate system, it was used a device produced by Aberlink, named coordinate measuring machine (CMM), with an uncertainty within the working space of 2 μm (Fig. 2c).



(a) (b) (c)

Fig. 2. (a) Nikon Coolpix L810 digital photo camera, (b) 3D calibration grid, (c) coordinate measuring machine (CMM)

2.3. Data processing

In order to obtain the image coordinates for the 3D calibration object control points, Lisa software was used. This is a digital photogrammetric software created by Dr.-Ing. Wilfried Linder, Bad Pyrmont – Hagen from Germany, that allows the measuring in images process. Therefore it has many fields of applications, like: agriculture and forestry, archaeology, architecture, coastal protection, disposal monitoring, geography and environmental sciences, hydrology, material testing, monument preservation, urban and regional planning [7].

The calibration process was made using the Matlab software. This is a high performance language for technical computing, developed by MathWorks, which integrates numerical computation, visualization and programming. It is used to analyze data, to develop algorithms, and create models and applications, allowing matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, Java, Fortran and Python.

In order to obtain the building 3D model, the images were processed with the PhotoModeler Scanner 6 software developed by Eos Systems Inc. Company from Vancouver, Canada. This software creates 3D models and allows accurate 3D measurements from photographs taken with most standard cameras (either digital or film), which represents a very cost-effective way of doing accurate 3D scanning, measurement and surveying. The 3D models are created and exported with photographic textures extracted from the original images.

3. Results and discussion

Usually, the calibration algorithms have traditionally employed reference grids, the calibration matrix K being determined using one or more images of a known object point array, such as checkerboard patterns. Commonly adopted methods are those of Tsai (1987), Heikkilä & Silven (1997) and Zhang (2000). These algorithms are all based on the pinhole camera model and include terms for radial distortion modelling. The principal characteristic of the pinhole camera model is the principle of collinearity, where each point in the object space is projected by a straight line through the projection center into the image plane. This model is only a approximation of the real camera projection and it is not valid when high accuracy is required. Therefore, a more comprehensive camera model must be used, which includes corrections for both radial and tangential lens distortions.

3.1. Image observations for the Nikon Coolpix L810 digital camera calibration

The first step in the camera calibration process is represented by image observations of the object. Having a 3D target, one image is enough to estimate the camera parameters through the calibration process and for this experiment it was used a single image, taken at 1 meter distance, using the minimum focal length (Fig. 3).

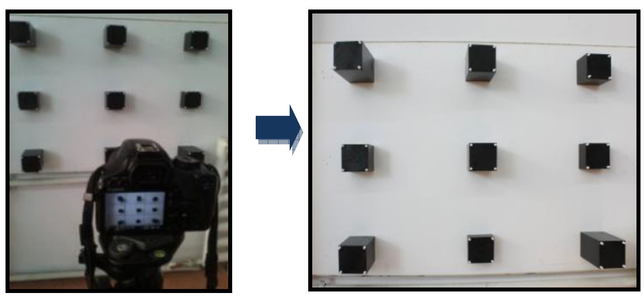


Fig. 3. Image observation of the 3D object, using the Nikon Coolpix L810 digital camera

3.2. Tsai calibration algorithm

The camera calibration based on Tsai's algorithm (1987) recovers the interior orientation (intrinsic parameters), the exterior orientation (extrinsic parameters), the distortion coefficient and also an image scale factor. The algorithm given by Tsai is a two-step method that can cope with either a single image or multiple images of a 3D or planar calibration grid, but grid point coordinates must be known. Its implementation needs corresponding 3D point coordinates and 2D pixels in the image.

For the present study, it was used a Matlab toolbox implementing the Tsai's calibration method, with the first term of radial distortion correction, accessed via www-cgi.cs.cmu.edu/afs/cs.cmu.edu/user/rgw/www/TsaiCode.html. There was used a single photo of the calibration object, at one meter distance, with a minimum focal length. In order to do the computations, there was used a number of 15 points with known 3D world and image coordinates.

The calibration process uses a two-stage technique. The first stage determines the extrinsic parameters: focal length, rotation matrix, scale factor and the translation vector, by solving a system of linear equations whose input is the coordinates of points in the calibration pattern, both in the image and in real world. The second stage computes the radial distortion factor, which cannot be determined from the calibration pattern [8].

3.3 Heikkilä & Silven calibration algorithm

The camera calibration model proposed by Heikkilä & Silven (1997) determines a set of camera parameters that describes the mapping between 3-D reference coordinates and 2-D image coordinates. These are the intrinsic parameters, such as focal distance (f), optical center point (u_o, v_o), correction of radial distortion (k_1, k_2), correction of decentering distortion (p_1, p_2) and the image scale factor (s_u), as well as the extrinsic parameters (r_{ij}, X_o, Y_o, Z_o).

For the present experiment a Matlab toolbox implementing the Heikkilä & Silven's method with the two terms for both radial and decentering distorsion correction was used. This Matlab toolbox is available at www.ee.oulu.fi/~jth/calibr/ and utilizes a new adjustement procedure for circular control points and a recurseve method for distorsion [9].

The entire calibration process is done in four steps. The first step is a linear parameter estimation of the camera parameters using a closed-form solution (DLT). The DLT method is based on the pinhole camera model, ignoring the radial and tangential distortion coefficients. In this first step it is solved the linear transformation from object coordinates to image coordinates.

The second step computes the distortion parameters by applying a nonlinear least square estimation technique. The camera parameters are estimated by minimizing the weighted sum of squared differences between the observations and the model. This step includes the transformation from the 3D camera coordinate system to ideal (undistorted) image coordinates.

The third step of the calibration procedure is represented by the correction for the asymmetric projection. This correction is applied to the center points of the circular control points, due to the fact that the perspective projection of a circular feature on the image plane will not remain circular, but an ellipse. In order to correct the projection error of the circular control points, the camera parameters are computed recursively.

The fourth step, image correction, is used to solve the back-projection problem, in order to determine the re-projected 3D coordinates recovering the line of sight from the observed image coordinates. The unknown parameters for the inverse model were computed by least-square method, using a generated grid of about 1000-2000 points, covering the whole image area.

3.4 Comparative analysis of calibrating algorithms

The camera calibration model proposed by Tsai is a two-stage process that computes the intrinsic and also the extrinsic parameters of the camera. This algorithm obtains the intrinsic parameters, such as focal distance (f), optical center point (u_0, v_0), correction of radial distorsion (k_1) and also the image scale factor that minimizes the measured image coordinates corresponding to known target point coordinates (s_x), as they are presented in Table 1.

Table 1. The Nikon Coolpix L810 digital camera intrinsic parameters obtained with Tsai's calibration algorithm, for the minimum focal length **f = 4 mm**

Focal length	f [mm]	u_0 [pixeli]	v_0 [pixeli]	k_1[mm]	s_x
f=4 mm	4.0557	2332.245	1734.104	$5.2417 \cdot 10^{-4}$	1.0025

Regarding to the Heikkilä & Silven's calibration algorithm, in the first three steps, there were computed the intrinsic parameters of the Nikon Coolpix digital camera, as shown in Table 2.

Table 2. The Nikon Coolpix L810 digital camera intrinsic parameters obtained by Heikkilä & Silven's calibration algorithm, for the minimum focal length **f = 4 mm**

Focal length	f [mm]	u_0 [pixeli]	v_0 [pixeli]	k_1 [mm]	k_2 [mm]	p_1 [mm]	p_2 [mm]
f=4 mm	4.0958	2345.857	1751.143	$7.2721 \cdot 10^{-4}$	$-3.3710 \cdot 10^{-5}$	$-1.2215 \cdot 10^{-3}$	$-2.5316 \cdot 10^{-4}$

In the fourth step of the camera calibration process, the unknown parameters for the inverse model are solved, the resulting errors caused by the back-projection model being represented as histograms in both horizontal and vertical directions [10].

After the calibration process of the Nikon Coolpix L810 digital camera, using Tsai and Heikkilä & Silven's calibration algorithms, a comparative analysis of the two different sets of intrinsic parameters was realized, the differences being presented in Table 3.

Table 3 - The comparative results of the calibration process of the Nikon Coolpix L810 digital camera, obtain by using Tsai and Heikkilä & Silven's calibration algorithm

Parameter	**Calibration method Tsai/ Heikkilä & Silven [mm]**	**Differences [mm]**	**Differences [%]**
Focal length	4.0557 / 4.0958	-0.0401	-0.9887
Principal point (x_p)	3.1746 / 3.1873	-0.0127	-0.4001
Principal point (y_p)	2.3779 / 2.3793	-0.0014	-0.0589

The distortions were computed at 4 mm in relation to the image center. The two profiles of the radial distortion, based on the computed intrinsic parameters using the Tsai and Heikkilä & Silven calibration algorithm, are represented in Fig.4.

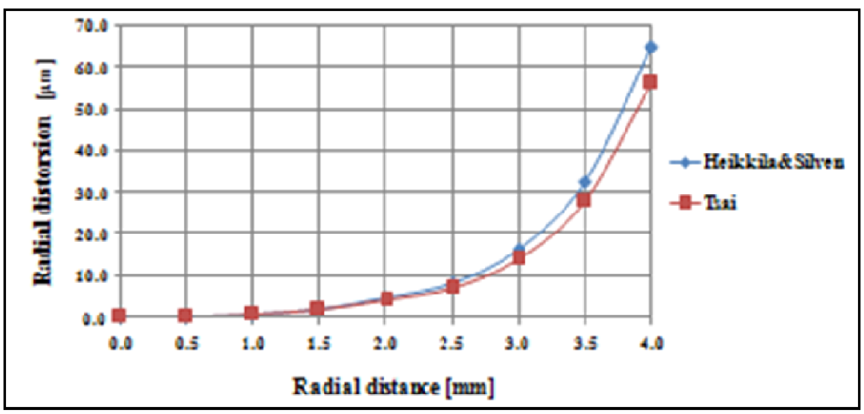


Fig. 4. Radial distortion profiles for the Nikon Coolpix L810 camera, computed using the calibration parameters resulted from Tsai and Heikkilä & Silven calibration algorithms

3.5 The 3D model creation

The 3D model of the *"Dosoftei House"* Museum of Iasi city, was created using *"PhotoModeler Scanner"* software. In a first phase, there were taken ten images around the building, from ten different positions, at different angles. The photos have 25%- 60% overlap and an angle of at least 20° between them. All images were taken with the minimum focal length of the Nikon Coolpix L810 camera lens (4 mm), mounting the camera on a tripod at each station point, for image stability.

Then, in a second stage, all photos were imported in the software and in the correlation process the method of manually match common features was used, every detail point or line of the building being manually marked and referenced.

When the correlation process was finished, the building 3D model was created, firstly using the intrinsic parameters computed by Tsai's calibration algorithm. In order to place the obtained 3D model in a real position in space, there were applied four transformations: a scaling and three rotations. Therefore, the 3D model was scaled and rotated, using the 3D known coordinates of three characteristic points, located on different facades, with sensible distance between them. The coordinates were determined by reflector less measurements made with a total station.

In order to get a real appearance of the building, the 3D model was textured, using the software's high- quality option.

(a) (b)

Fig. 5. The *"Dosoftei House"* 3D model, created in "PhotoModeler Scanner" software (a) perspective view of the main facade, (b) perspective view of the north-east facade

Secondly, it was obtained the 3D model of the "Casa Dosoftei" museum, using the intrinsic parameters computed by Heikkilä & Silven's calibration algorithm. It was used the same project, following the same steps, the only difference being the replacement of the calibration parameters.

3.6 Comparative analysis of 3D models

In order to analyze the accuracy of these two calibration algorithms, an evaluation of the building 3D digital models obtained using the "PhotoModeler Scanner" software, was made. Therefore, there were pointed out the differences between the values of two sets of coordinates of 20 characteristic points of the building, like: building corners, window edges, doors, etc., as resulted from total station measurements and by digital image processing, as shown in Table 4.

The plane rectangular coordinates were determined in the National Projection System, named "Stereographical on unique secant plan-1970" and the normal altitudes in the „Black Sea 1975" reference system for heights, through the GNNS technology using the South S82-V GNSS Rover.

In order to make the computations, the real coordinates rigorously obtained with the Leica TCR 407 total station were used as a reference base.

Table 4. The differences between the two sets of coordinates

Point no.	Differences - PhotoModeler (Tsai) – Total Station			Differences - PhotoModeler (Heikkilä & Silven) – Total Station			RMSE (m)	
	ΔX (m)	ΔY (m)	ΔZ (m)	ΔX (m)	ΔY (m)	ΔZ (m)	PhotoModeler - Tsai	PhotoModeler Heikkilä & Silven
1	-0.038	0.196	-0.170	0.035	0.020	0.020	0.263	0.045
2	0.166	-0.080	0.000	0.167	-0.060	0.000	0.184	0.177
3	-0.016	0.026	-0.018	-0.131	0.263	0.040	0.035	0.296
4	0.018	0.025	0.039	-0.061	0.091	-0.007	0.050	0.110
5	0.038	0.014	-0.016	-0.065	-0.033	-0.033	0.043	0.080
6	0.048	0.029	-0.097	0.049	0.025	0.101	0.112	0.115
7	0.041	0.216	-0.176	-0.034	-0.005	-0.025	0.282	0.042
8	0.018	0.031	-0.075	0.011	-0.029	0.083	0.083	0.089
9	0.036	0.146	-0.047	-0.070	-0.045	0.020	0.158	0.085
10	-0.019	0.078	0.049	0.070	0.069	-0.257	0.094	0.275
11	-0.035	-0.278	-0.245	0.107	-0.026	-0.103	**0.342**	0.151
12	-0.037	-0.015	-0.073	0.071	0.032	-0.261	0.083	0.272
13	-0.038	0.005	-0.181	-0.099	-0.063	-0.115	0.185	0.164
14	-0.036	-0.156	-0.025	0.048	0.111	-0.290	0.162	0.314
15	-0.146	0.031	-0.029	-0.121	0.296	0.028	0.152	0.322
16	-0.087	0.028	-0.030	-0.011	0.011	0.029	0.096	0.033
17	-0.103	0.026	-0.017	-0.043	0.244	0.009	0.107	0.248
18	-0.188	0.038	-0.152	-0.193	0.250	-0.150	0.245	**0.350**
19	-0.282	0.037	-0.190	-0.291	0.010	-0.294	0.342	0.320
20	0.039	0.031	-0.234	-0.031	0.069	-0.038	0.240	0.084
							0.163	**0.179**

The results show the maximum differences of 28.2 cm on the X coordinate, 27.8 cm on the Y one and 24.5 cm on Z axis for the model created using the parameters obtained with Tsai calibration algorithm and 29.1 cm on X coordinate, 29.6 cm on Y and 29.4 cm on Z axis, for the second model, based on Heikkilä & Silven's camera calibration algorithm.

The *Root Mean Square Error* was computed, using the following formula:

$$RMS_{error} = \sqrt{(X_r - X_i)^2 + (Y_r - Y_i)^2 + (Z_r - Z_i)^2} \tag{1}$$

where: X_r, Y_r, Z_r – the coordinates obtained with the total station TCR 407 Ultra,
Xi, Yi, Zi – the coordinates obtained by digital 3D models interrogation.

From Table 4 it can be noticed that the greatest total error for the model created using the Tsai's calibration parameters is of 34 cm, while for the other one is of 35 cm. After the results analysis, the *Cumulative Root Mean Square Error* for these two 3D models was computed and it has the value of 16 cm for the first model and of 18 cm for the second one.

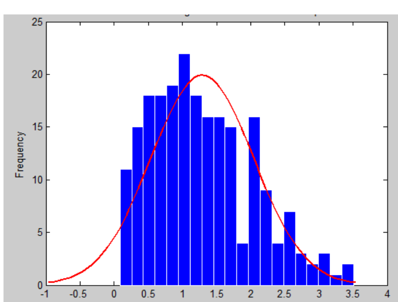


Fig. 6. The errors distribution histogram of the measured detail points image coordinates

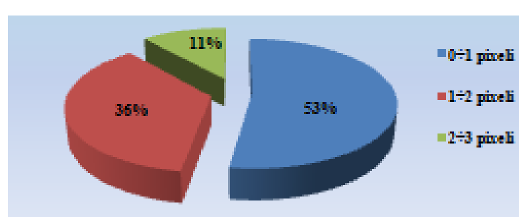


Fig. 7. The error repartition of the building detail points image coordinates

For the resulted 3D model, obtained by using the calibration parameters computed with Tsai calibration algorithm, the errors distribution histogram of the image coordinates of the detail points, was calculated as it can be seen in Fig. 6 and also the error repartition of the building characteristic points image coordinates (Fig. 7).

Finally, the overall residual of the project using the parameters computed with Tsai's calibration algorithm, was of 1.312 pixels.

The angles between the projection rays of the detail points range between 9°23'12" and 89°43'21", with an average of 50°13'23" as they are shown in intervals of 20° in Fig. 8.

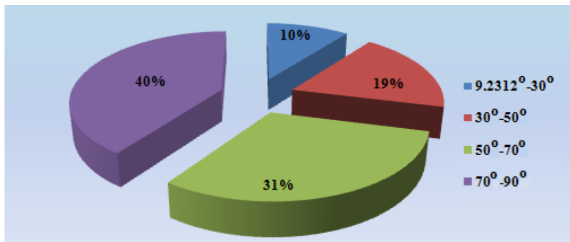


Fig. 8. The repartition of the angles between the projection rays, used in points coordinates computation, based on calibration parameters obtained with Tsai's calibration algorithm

For the project using the calibration parameters computed with the Heikkilä & Silven's calibration algorithm, the overall residual was of 1.401 pixels. Also, it was realised the error distribution histogram of the detail points image coordinates (Fig. 9) and their repartition (Fig. 10).

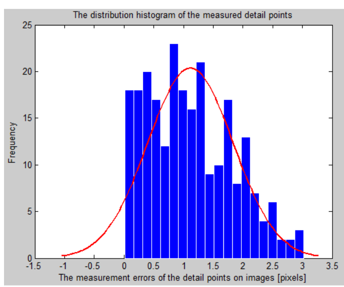


Fig. 9. The errors distribution histogram of the measured detail points image coordinates

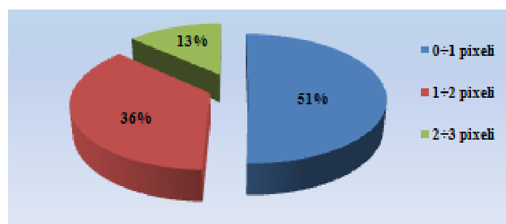


Fig. 10. The error repartition of the building detail points image coordinates

In the case of the distribution of medium angles between the projection rays, corresponding to building characteristic points, a chart based on the angles values grouped in intervals of 20° is shown in Fig. 11. The angles range between 12°06'71" and 89°94'93", with an average of 52°24'19".

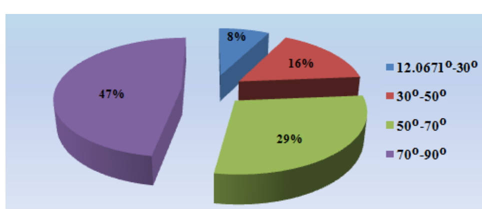


Fig. 11. The repartition of the angles between the projection rays, used in points coordinates computation, based on calibration parameters obtained with Heikkilä & Silven's calibration algorithm

4. Conclusions

The camera calibration process has always been an essential component of photogrammetric measurement, especially used in close-range measurements. In order to extract precise and reliable 3D metric information from images, an accurate camera calibration and orientation procedures are necessary. A camera is calibrated when parameters like: the principal distance, the principal point offset and lens distortion parameters are known. In many applications, especially in computer vision domain, only the focal length is determined, but when high-accuracy photogrammetric measurements are needed, all calibration parameters must be known.

This article presents a comparative study on two different calibration algorithms developed by Tsai and Heikkilä & Silven applied in the Nikon Coolpix digital camera calibration process. A single image of the 3D calibration object was used in both cases. In order to estimate the camera parameters, the initial data for these two algorithms was represented by a set of 3D points and their corresponding 2D projection on an image plane.

In order to compare the accuracy provided by each algorithm, the same set of test points has been used and the 3D model of the same building, *"Dosoftei House"* Museum of Iasi city, fact which allows the results to be reliably compared.

The RMSE has value of 16 cm for the 3D model created using the Tsai calbration parameters and of 18 cm for the one created using the Heikkilä&Silven calbration parameters.

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