Study of Camera Calibration Process with Ray Tracing

A.-S. Poulin-Girard[1,2], X. Dallaire[1], A. Veillette[1], S. Thibault[1,*] and D. Laurendeau[2]
[1]Centre d'optique, photonique et laser, Département de physique, de génie physique et d'optique
[2]Laboratoire de vision et systèmes numériques, Département de génie électrique et de génie informatique
Université Laval, Québec (QC), Canada G1V 0A6

ABSTRACT

Camera calibration is essential for any optical system used to obtain 3D measurements from images. The precision of the 3D depth estimation relies on an appropriate camera model and the accurate estimation of model parameters. These parameters are sensitive to environmental conditions and it is well established that a vision system should be calibrated in operating conditions. This is not always possible since the calibration process is often tedious and time-consuming. Unfortunately, the use of poorly estimated calibration parameters for 3D reconstruction and measurements may lead to suboptimal performance of the system and inaccurate depth estimation.

This paper presents a technique using an existing camera model and optical design software to perform calibration simulations. This virtual calibration technique allows for a study of the impact of environmental conditions on the calibration parameters. Using this procedure, it is also possible to predict the statistical behavior of the calibration parameters considering the chosen fabrication processes and tolerances. It can assist vision scientists in the choice of the optical system that best meets the requested precision of the 3D reconstruction. This technique could eventually be integrated in the lens design process to create more reliable optical systems that could be calibrated and used in a range of environmental conditions with a very small variation of their calibration parameters.

Keywords: Camera calibration, optical design software, tolerancing, lens design

1. INTRODUCTION

Camera calibration is a crucial step in metrology applications such as 3D measurements. It determines the mathematical link between the object space and the image plane. Accurate 3D depth estimation performed with a stereoscopic system relies on a robust calibration process as well as on a camera model that adequately describes the imaging system. Even if these criteria are met, the quality of depth estimation also depends on other factors such as environmental conditions like pressure, vibration, and temperature. It is widely acknowledged that an imaging system should be calibrated in the operating conditions of the targeted environment in which it is to be used. Even if calibration is performed in the laboratory at operating conditions for a system that will be used in another location, changes in the calibration parameters can happen during transportation.

Some experimental studies have been performed regarding the impact of temperature on calibration parameters [1-3]. However, similar experimental studies on the impact of various environmental conditions and transportation of the system would be extremely tedious to perform. To address this issue, a virtual calibration technique has been developed [4]. It uses optical design software, the lens prescription as well as a calibration toolbox. It is flexible and allows the user to work with different types of lenses and calibration toolboxes.

To highlight the possibilities of this virtual technique, this paper focuses on the impact of temperature and tolerancing on the calibration parameters. A description of the lens, the calibration model and the toolbox used is given and the virtual calibration technique is explained. Results from simulations are presented.

2. LENS AND CALIBRATION MODEL

As mentioned in the introduction, this technique is not specific to an application, a type of lens or a calibration model. Previous simulations have been made [4] with a wide angle lens and the *OCamCalib* toolbox [5]. To demonstrate some possibilities of this technique with a different toolbox, the design file of the lens 58-000 from Edmund Optics is used in this paper. Its focal length is 8.5 mm and it can cover a full field of view up to 46° on a 1/2.5″ sensor.

*simon.thibault@phy.ulaval.ca; phone 1-418-656-2131 x 12766; http://lrio.copl.ulaval.ca

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Jean-Yves Bouguet's *Camera Calibration Toolbox* for Matlab is a widely used calibration toolbox for traditional cameras [6]. It uses the pinhole camera model introduced by Brown [7]. In this model, the object vector $[X_C;Y_C;Z_C]$ is used to obtain the normalized image coordinates x_n as expressed in equation (1).

$$\begin{bmatrix} x_n \\ y_n \end{bmatrix} = \frac{1}{Z_C}\begin{bmatrix} X_C \\ Y_C \end{bmatrix} \tag{1}$$

To account for radial and tangential distortions, a correction function is introduced. The new coordinates are expressed as a function of the distortion coefficients k_i as shown in equation (2), with the radial image coordinate being defined as $r_n^2 = x_n^2 + y_n^2$.

$$\begin{bmatrix} x_d \\ y_d \end{bmatrix} = \left(1 + \boldsymbol{k_1} r_n^2 + \boldsymbol{k_2} r_n^4 + \boldsymbol{k_5} r_n^6\right)\begin{bmatrix} x_n \\ y_n \end{bmatrix} + \begin{bmatrix} 2\boldsymbol{k_3} x_n y_n + \boldsymbol{k_4}\left(r_n^2 + 2x_n^2\right) \\ \boldsymbol{k_3}\left(r_n^2 + 2y_n^2\right) + 2\boldsymbol{k_4} x_n y_n \end{bmatrix} \tag{2}$$

Pixel image coordinates and distorted image coordinates are related by the intrinsic matrix K.

$$\begin{bmatrix} x_p \\ y_p \\ 1 \end{bmatrix} = \underbrace{\begin{bmatrix} \boldsymbol{fc_x} & \boldsymbol{\alpha_c}\,\boldsymbol{fc_x} & \boldsymbol{cc_x} \\ 0 & \boldsymbol{fc_y} & \boldsymbol{cc_y} \\ 0 & 0 & 1 \end{bmatrix}}_{K}\begin{bmatrix} x_d \\ y_d \\ 1 \end{bmatrix} \tag{3}$$

The calibration parameters are the focal lengths fc_x and fc_y, the principal point coordinates $(cc_x;cc_y)$, the skew coefficient α_C and the distortion coefficients k_i that appear in bold fonts in equation (2) and (3). Today's digital cameras do not justify the use of all these calibration parameters. The skew coefficient α_C is set to 0 as well as coefficient k_5. Therefore, eight calibration parameters are used in this reduced model that is valid for low and moderate field of view cameras.

The calibration procedure presented in this paper uses the estimation of planar homographies to initialize the calibration parameters [8] except for distortion coefficients. Calibration parameters estimation is refined and distortion coefficients are obtained with a technique using the orthogonality of vanishing points in an image [9]. The mean reprojection error is then computed. This value represents how closely the model and the calibration parameters estimate the image points in comparison with the real image point from the calibration targets. This error is minimized during the calibration process and indicates the quality of the calibration.

3. VIRTUAL CALIBRATION TECHNIQUE

In an experimental calibration process, several pictures of a known planar target in different poses are taken. The planar target contains control points, the position of which is used to determine the optimal calibration parameters. When the images are loaded, corner detection is performed. This process creates a set of variables specific to the toolbox used such as the coordinates of the control points, the size of the image and the number of images. Since there are no real images in our virtual technique and therefore no corner detection process, the set of variables is generated artificially because they are required for the calibration process.

The virtual calibration technique requires the creation of virtual targets. Their specifications, such as the number of control points and the distance between two neighbouring control points, have to be set. Matlab is used to create the targets and the field angle of each control point on each target is obtained using direction cosines [10]. The corresponding image coordinates are calculated by ray tracing in Zemax®. Although it would be more realistic to use the position of the centroid for each point, only the chief ray is used for the sake of computational efficiency. The image coordinates are transformed into pixel coordinates and, along with the necessary set of variables mentioned above, are used to perform calibration. The image is sampled with a pixel pitch of 2.2 μm which is a realistic value for a 1/2.5″ sensor. Fig. 1 shows a schematic of the process.

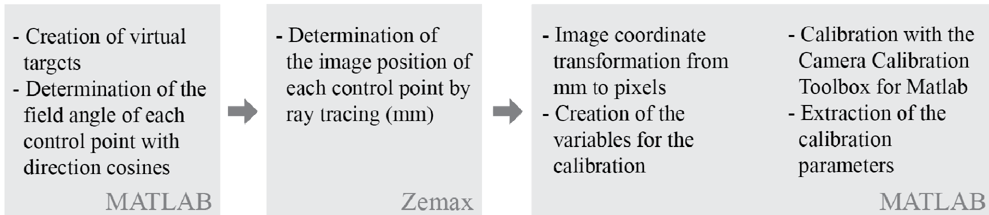

Fig. 1 Flow chart of the virtual calibration technique

For this paper, 10 targets were created. Each of them contains 11X11 control points with a distance of 20 mm between two consecutive points. The targets were positioned relatively close to the lens, at a mean distance of 500 mm, which can still be considered infinity compared to the focal length of 8.5 mm. Fig. 2 shows the simulated targets in object space. Fig. 3 shows the corresponding virtual images.

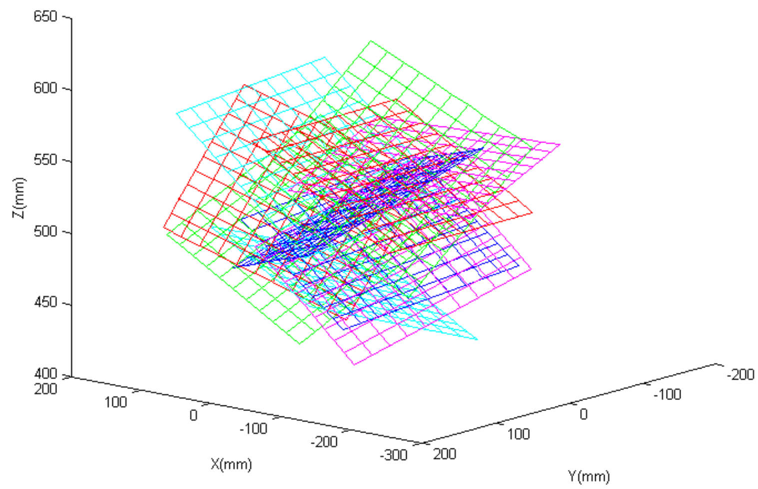

Fig. 2 Simulated targets in object space. The pinhole origin is located at (0;0;0).

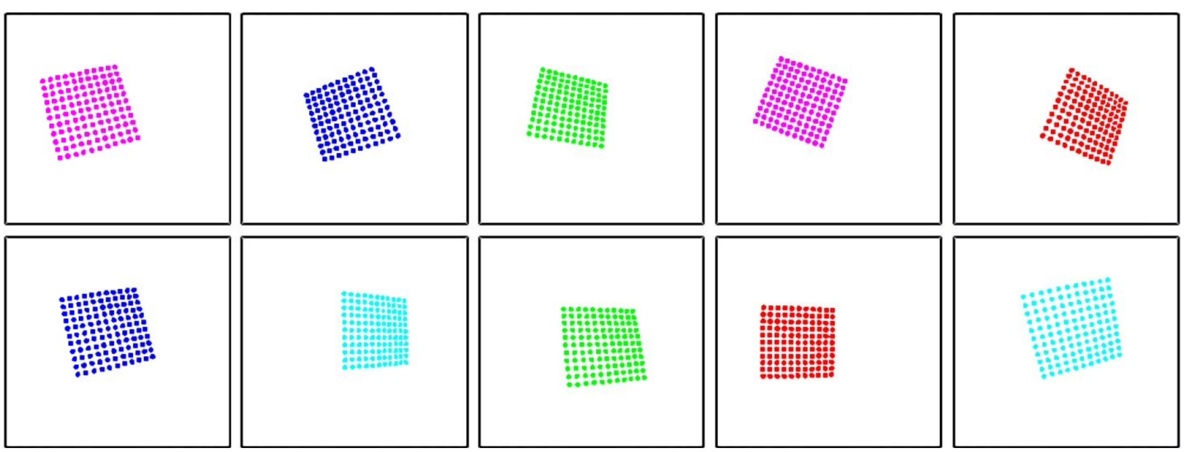

Fig. 3 Virtual images corresponding to the simulated targets shown in Fig. 2

4. CALIBRATION RESULTS

This section focuses on the impact of temperature and tolerancing on the calibration parameters. Many other factors such as pressure, light polarization or decentering and tilt could be studied with the same virtual camera calibration technique.

4.1 Uniform temperature variation

To highlight the impact of temperature on the calibration parameters, Zemax® multi-configuration editor is used. The air space thermal coefficient of expansion is set to take into account the effect of the aluminum mount for temperatures between -250°C and 250°C. Standard values for *dn/dT* and thermal expansion coefficient are used on the entire temperature range even if they are not defined for extreme temperature values. Standard values are used on the entire temperature range. A Zemax® macro is used to analyze independently each configuration and determine the position of each control point's chief ray. Since the variation of temperature does not induce decentering or tilt of any elements, the principal point coordinate should not vary, only the focal lengths and distortion coefficients could be modified. Simulations show that the principal point coordinates are extremely stable for every temperature. The mean position (2997.97148 ; 2998.027334) is very close to the nominal position (2997.97146 ; 2998.027326), the real principal point coordinates being (3000 ; 3000). Distortion parameters k_3 and k_4 accounting for tangential distortion undergo small variations of less than 5×10^{-6}. The focal lengths and radial distortion parameters k_1 and k_2 have the behavior shown in Fig. 4 with respect to the temperature variation.

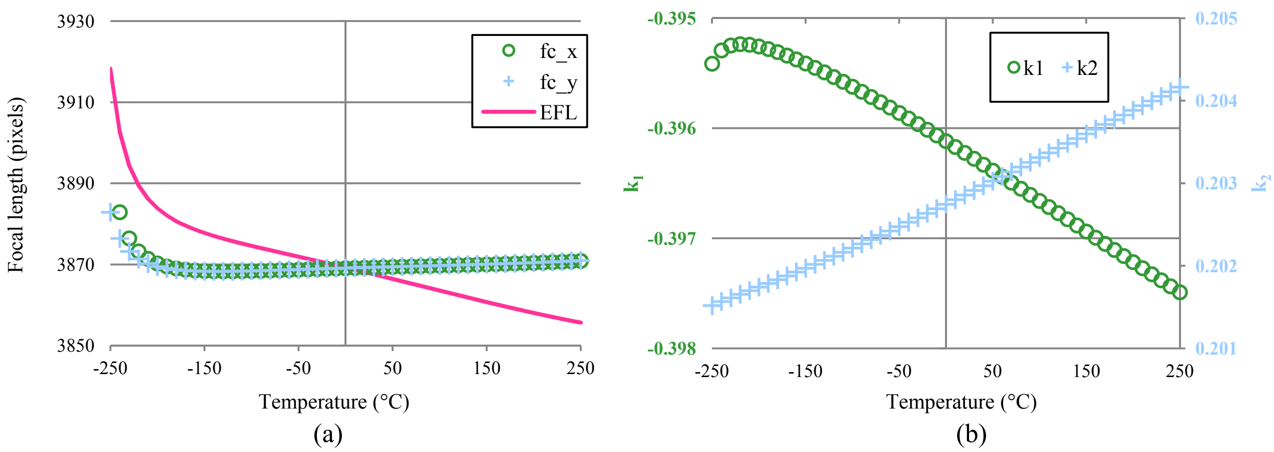

Fig. 4 (a) Calibration focal lengths and EFL obtained with Zemax® and (b) distortion coefficient k_1 and k_2 as a function of the temperature

The calibrated focal lengths along x and y have the same behavior. However, the values are different from the effective focal length (EFL) calculated in Zemax®. The calibration algorithm cannot be used to measure the physical focal length or any other physical characteristics of an optical system. It finds the optimal solution (calibration parameters) for a set of data (virtual target image coordinates). This means that it would not be possible to use a set of parameters that would include calibration parameters and parameters calculated with optical design software.
Distortion parameters k_1 and k_2 vary with the temperature as expected. Along with the variation of the focal lengths and the consistency of the principal point coordinates, it shows that the model describes well the optical system for thermal simulations.

4.2 Temperature gradient

Another typical thermal condition is temperature gradient. In this case, the front element was set at a temperature of 10°C and the last element at 35°C, mimicking a situation where the front lens would be at a lower temperature than the sensor. The discrete gradient is shaped by the optical system elements. As in the case of a uniform temperature, the temperature gradient does not significantly modify the principal point position. In this case, the distortion coefficients are almost identical to the nominal values. The calibration focal lengths are similar to the nominal values in both x and y

(3870.3 pixels versus 3869.25 pixels). This behavior is coherent with Fig. 4 (a) where the focal lengths are relatively constant around the nominal value for temperature over -150°C.

4.3 Tolerancing

Tolerances analysis allows the manufacturer to build optical systems that will meet a set of specifications despite the presence of perturbations. Tolerances are applied to the optical design parameters such as element and surface tilt, decentering and refraction index. For the purpose of this study, the manufacturer tolerances are used for glass material, radius, thickness and surface irregularity [11]. Other perturbations were added: an element decentering of 25 µm, an element tilt of 25 µm/D and a surface tilt of 5 µm/D, with D being the diameter of the lens. The Monte Carlo method is used to create 20 perturbed versions of the nominal design that meets a RMS spot size of less than twice the nominal design RMS spot size. Using the targets shown in Fig. 2, virtual camera calibration was performed to assess how the perturbations affect the camera calibration results. Table 1 shows the mean, minimum and maximum values of each parameter as well as their standard deviation.

Table 1 Statistics for the calibration parameters for 20 perturbed versions of the nominal design

Parameters	Nominal value	Mean	Maximum	Minimum	Standard deviation
fc_x *(pix)*	3869.26	3872.31	3896.12	3858.80	11.50
fx_y *(pix)*	3869.24	3872.34	3896.03	3853.74	11.48
cc_x *(pix)*	2997.97	2997.07	3017.22	2983.91	8.81
cc_y *(pix)*	2998.03	2997.63	3006.65	2984.11	6.96
k_1	-0.3962	-0.3961	-0.3948	-0.3974	6.67×10^{-4}
k_2	0.2029	0.2011	0.2032	0.1995	9.31×10^{-4}
k_3	2.70×10^{-6}	-7.05×10^{-6}	2.64×10^{-4}	-3.70×10^{-4}	1.71×10^{-4}
k_4	3.16×10^{-6}	-5.63×10^{-6}	3.20×10^{-4}	-3.10×10^{-4}	1.51×10^{-4}

The calibrations parameters do not seem to follow any specific distribution. However, they vary around the nominal value within a certain range. Depending on the distribution of the calibration parameters, it could be possible to use the data for 3D reconstruction for any build of a lens for applications not requiring high precision. Further tests would allow to decide if this approximation for depth estimation is valid for a specific model of lens and meets the precision requirements for a given application.

5. CONCLUSION

Virtual camera calibration is a flexible and useful process. In this paper, the possibilities of this technique have been highlighted with simulations regarding temperature and tolerancing with 10 calibration targets. The results show that the behavior of the estimated camera model parameters is coherent with the behavior of the corresponding physical parameters. Virtual calibration simulation at different temperatures show a change in the focal length and distortion coefficients but not in the principal point coordinates. Statistics regarding several toleranced systems demonstrate that the calibration parameters vary in a relatively narrow range around their nominal value. To date, the technique has been tested with two different sets of lens and calibration toolbox and has proven to be in agreement with the actual physical behavior. However, it was also found that physical parameters such as the focal length obtained with Zemax® could not be used as calibration parameters. Keeping some parameters from the optimization process and adding physical parameters value to account for environmental conditions would not lead to an optimal solution for 3D depth estimation.

The virtual calibration technique offers additional possibilities, especially to make the calibration process easier and guide the user in the experimental process. Optimization of target parameters such as the number of control points, the distance between two consecutive control points as well as the range of positions at which the targets should be placed could be performed in order to obtain more accurate calibration results. The impact of the target parameters, position and orientation could be studied to verify if different configurations are equivalent. If it is not the case, the technique could help provide guidelines for better calibration. The link between the mean reprojection error and the reconstruction error could also be explored. This technique could also be extended to a calibration toolbox using non-planar targets.

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