Model-based adaptive estimation of camera matrices for variable-focus optical metrology applications

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The use of variable-focus optics in optical metrology application allows the working range of cameras to be enhanced. However, the validity of the model-based camera calibration, which is important for triangulation, is limited to the corresponding focus setting This paper presents an approach to describe the calibration parameters over the focus range.

1 Introduction

The working range of optical and, in particular, triangulation-based measuring systems is often limited by the depth of field properties of the optics used. An increase in the depth of field range by reducing the aperture is offset by a lower light yield and thus the need for a longer exposure time. The use of variable-focus optics allows the working range to be adapted. However, the validity of the model-based camera calibration, which is important for triangulation, is limited to the corresponding focus setting, especially for optics whose focal length changes with the focus setting. This paper presents an approach to describe the calibration parameters over the entire focus range of a lens utilizing a widely adopted method of camera calibration. The precise estimation of the parameter curve requires a high density of interpolation points, which is associated with a considerable calibration effort. In order to reduce the effort for a large number of interpolation points, an automation of the image acquisition is implemented.

2 Experimental setup

In this setup a focusable camera is used in an adaptive triangulation sensor. The experimental system can be adapted to working distances within in the range of 0.4m to 1.7m. The laser line can be repositioned by a mirror rotated by a piezo rotation stage.

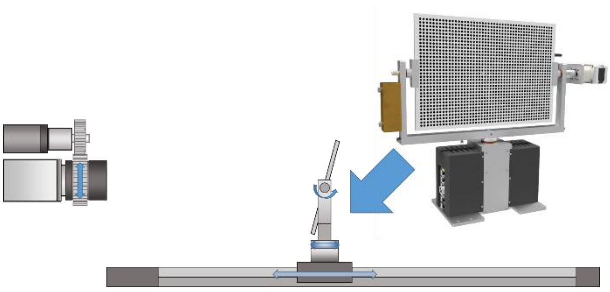

Fig. *1 Schematic illustration of the focusable camera and the automated image acquisition.*

The camera sensor used in this setup is a 1inch type, monochromatic, global shutter, CMOS Sensor with 9 million pixels. A lens with a focal length of 75mm and a minimal focussing distance of 0.25m is attached to the camera. The chosen f-stop of the aperture is fixed to f/8. The focussing of the lens to the desired working distance is achieved through a contrast based autofocus algorithm and a stepper motor that rotates the lenses manual focus ring over a gear step.

Although a sufficiently low residual error of the calibration is already achievable with a few poses, to allow for outlier removal, the aim is to acquire 25 poses per working distance. Furthermore 20 working distances are recorded for a robust estimation of the parameter curve. To reduce the effort considerably, the image acquisition is automated using a linear axis and a two-axis positioning unit, as shown in Fig. 1.

3 Camera calibration

The basic principle of a camera can be described by the pinhole camera model, where light rays fall onto the image plane through a small aperture. As a result, a point from the world coordinate system X, Y, Z will be projected onto the image plane u, v as following:

$$s\begin{pmatrix} u \\ v \\ 1 \end{pmatrix} = \begin{pmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 0 \end{pmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \quad (1)$$

Thereby the extrinsic parameters of the camera are r, t and the intrinsic parameters are the 2D- components of the focal length f and the optical center c. Determining these parameters is the goal of most model-based camera calibration procedures. The validity of the pinhole camera decreases where optical aberrations are present. Especially the effect of distortion has to be accounted for. The radial

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distortion of the image point x, y can be represented as follows [1]:

$$\begin{aligned} x_{dist\_rad} &= x(1 + k_1 r^2 + k_2 r^4 + k_3 r^6) \\ y_{dist\_rad} &= x(1 + k_1 r^2 + k_2 r^4 + k_3 r^6) \end{aligned} \quad (2)$$

The tangential distortion can be represented similarly with two distortion coefficients. Overall there are five distortion coefficients and four camera parameters to be determined in the camera calibration. In one of the most common methods of calibration, described by *Zhang* [2], this is achieved by acquiring several poses of a geometrically known planar calibration target. Here, a target is used with circular feature points which are detected with image processing. A change of the focus setting of an objective lens typically leads to a change in both the intrinsic camera parameters and the distortion coefficients. In order to be able to describe the parameters over the entire focus range of the camera, they must therefore be determined as a function of the focus position.

4 Modell-based parameter estimation

In a first step a camera is calibrated for each focus distance with the acquired feature points, according to *Zhang* [2]. Distortion Parameters are not considered in this first step. Outlier points and poses are removed based on the resulting reprojection error which is the deviation between projected object points and the acquired image points. A curve is fitted to the parameters resulting from the individual camera calibrations. The focal lengths are described by third degree functions and the parameters of the optical centre are described by second degree functions. All Parameters are dependent on the motor position of the autofocus-device. Subsequently the individual cameras are calibrated again. The starting values estimation is given by the fitted functions. In this second calibration the distortion is determined and furthermore, camera centre parameters are fixed to their starting values. Finally, third-degree functions are fitted again to values of the focal lengths and additionally to the distortion coefficients, with a third-degree function as well.

5 Results and discussion

The fitting of the functions to the parameters of the focal length, shown in Fig. 2 is executed with small deviation, which is below 0.1mm. Both spatial components overlap almost identically. In addition, only a negligible change occurs in the second calibration. The focal length resulting from the calculation differs from the value specified by the manufacturer strongly. Close-up focal length is above 100mm at an approx. workings distance of 40cm. The focal length decreases to approx. 80mm at with an increase of the focus distance to approx. 170cm.

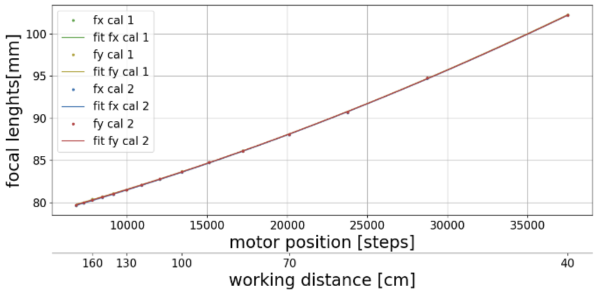

Fig. 2 *Course of the functions fitted to the focal lengths*

The fit to the parameters of the optical centre deviates noticeably from these parameters at larger workings distances. Furthermore, the optical centre shifts up to 200px between the nearest and the farthest working distance.

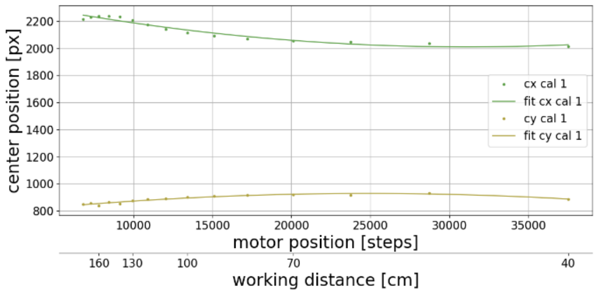

Fig. 3 *Course of the functions fitted to the parameters of the optical centre*

The fit of the distortion parameters, not shown, also has noticeable deviations. However, especially the tangential parameters negligibly small (<0.001). Deviations of the here more relevant radial distortions are smaller.

The results of the focal length illustrate the presence of the effect of focus breathing and the necessity to determine the camera parameters in relation to the focus setting. The shift of the optical centre is especially relevant for triangulation applications. An experiment has shown that the intrinsic parameters shift can influence the extrinsic camera location determination. In this type of application, it can be more useful to fix the centre parameters to single values. In conclusion, the description of parameters essential for metrology applications can be expressed in relation to the focus setting through function fitting.

References

[1] D. C. BROWN, “Close-Range Camera Calibration,” *Photogrammetric Engineering*, no. 37, pp. 855–866, 1971.

[2] Z. Zhang, “A flexible new technique for camera calibration,” *IEEE transactions on pattern analysis and machine intelligence*, vol. 22, no. 11, pp. 1330–1334, 2000.

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