

# A new dimension in geometric camera calibration

Dietmar Wueller, Image Engineering, Kerpen, Germany

## Abstract

There are many test charts and software to determine the intrinsic geometric calibration of a camera including distortion. But all of these setups have a few problems in common. They are limited to finite object distances and require large test charts for calibrations at greater distances combined with powerful and uniform illumination. On production lines the workaround for this problem is often times the use of a relay lens which itself introduces geometric distortions and therefore inaccuracies that need to be compensated for.

A solution to overcome these problems and limitations has originally been developed for space applications and has already become a common method for the calibration of satellite cameras. We have now turned the lab setup on an optical bench into a commercially available product that can be used for the calibration of a huge variety of cameras for different applications. This solution is based on a diffractive optical element (DOE) that gets illuminated by a plane wave generated with an expanded laser diode beam. In addition to the conventional methods the proposed one also provides the extrinsic orientation of the camera and therefore allows the adjustment of cameras to each other.

## Introduction

Many applications require the geometrical characterization and calibration of cameras. In photogrammetry, distances are measured in images. In conventional photography distortion is measured and compensated in the image processing pipe and in automotive applications distances to objects are calculated based on the measured geometrical characteristics of the camera or a stereo camera pair.

In order to characterize the geometric mapping by a camera of an original scene onto the imaging plane a regular grid of structures like a checkerboard, a dot pattern or a grid of crosses is used quite often. These structures are printed on a test chart and then photographed with the camera under test. Depending on the field of view of the camera and the intended object distance for the calibration, the test chart needs to have a certain size and the size and number of grid points needs to be selected based on the required accuracy and the sampling rate (pixel count) of the camera.

To overcome the limitation to finite object distances with the use of test charts for the geometric calibration the use of relay lenses is a common approach. But these relay lenses are not perfect and therefore introduce geometric errors to the image as well, which need to be compensated in the measurement.



Figure 1. An example where geometric calibration is required is the distance analysis in automotive imaging.

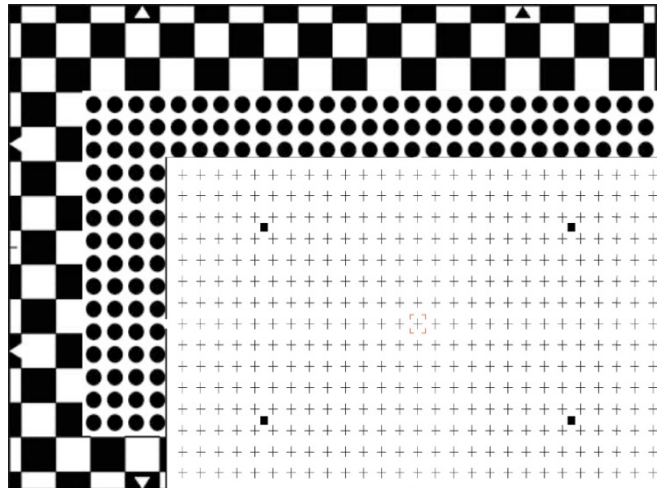


Figure 2. Typical structures used for test chart based geometric calibration.

## The principle of DOE based geometric characterization

For the DOE based geometric calibration a laser is used. The wavelength of the laser and the diffractive optical element itself define the grid of points that is created. In principle any wavelength can be used as long as it is stable over time and the DOE is suitable for it. This means a calibration is possible for any wavelength in the visible range and also for wavelength in the near IR if required.

The beam coming from the laser is expanded by a high-quality collimator and the optical plane wave falls on to the DOE. The DOE generates the regular grid of points that virtually originate from infinity. These points are imaged by the camera and form a grid on the imaging plane. Depending on the orientation of the grid to the expanded laser beam, the camera to the laser beam and the camera distortion the grid is scaled, modified and shifted from its ideal structure. The modification from the ideal grid allows to calculate

the orientation of the DOE, the focal length of the camera, the principle point of the camera, the orientation of the camera and its distortion.

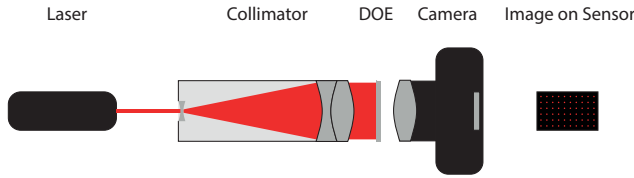


Figure 3. The principle of the DOE based geometric characterization.

## From the DOE to the image

As described by Bauer et al. [1] the formation of the grid in projection space can be calculated using the homogeneous coordinates  $d = [X, Y, Z, 0]^T$

$$d = \left[ \lambda F_x + r_x, \lambda F_y + r_y, \left( 1 - (\lambda F_x + r_x)^2 - (\lambda F_y + r_y)^2 \right)^{1/2}, 0 \right]^T \quad (1)$$

$$r = [\sin(\beta), -\sin(\alpha)\cos(\beta), \cos(\alpha)\cos(\beta)]^T \quad (2)$$

with  $\lambda$  being the wavelength of the laser and  $F$  the frequency of the grating calculated as  $F_{x,y} = n_{x,y}/g_{x,y}$  with  $n$  being the diffraction order and  $g$  the grating constant.

$r$  describes the correction for a non-perpendicular angle of incidence onto the DOE.

When the camera comes into play  $d$  has to be corrected for camera rotation  $R$  (matrix) and translation  $t$  but the equation shows that the image is invariant of translation  $t$ .

$$d' = \begin{bmatrix} R & t \\ 0 & 1 \end{bmatrix} d \quad (3)$$

Now the homogeneous coordinates need to be projected onto the imaging plane of the camera using:

$$\begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} X'/Z' \\ Y'/Z' \\ 1 \end{bmatrix} \quad (4)$$

And the camera matrix  $K$  describes the impact of focal length  $f$  and principal point  $u_0, v_0$  using the pinhole model.

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = K \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \quad (5)$$

with

$$K = \begin{bmatrix} f & 0 & u_0 \\ 0 & f & v_0 \\ 0 & 0 & 1 \end{bmatrix} \quad (6)$$

Last but not least the camera distortion comes into play. In most cases a radial model can be used and described as:

$$\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} u_0 \\ v_0 \end{bmatrix} + f \begin{bmatrix} x \\ y \end{bmatrix} (1 + k_q r^2 + k_q r^4 + k_q r^6 + \dots) \quad (7)$$

$$\text{with } r = x^2 + y^2$$

In case for example of a windshield in front of a camera in an automotive application the distortion introduced cannot be described by a rotational model. In these cases, a modified approach like the local geometric distortion described in ISO 17850 [2] needs to be used.

## The unique characteristics

From the measurement and calculation described, the following values can be derived:

- The principle point  $u_0$  and  $v_0$
- The focal length  $f$
- The distortion coefficients  $k_1, k_2, k_3$
- The DOE angle in relation to the incident expanded plane laser beam  $\alpha$  and  $\beta$
- And the camera angles in relation to the incident expanded plane laser beam  $\omega, \varphi, \kappa$

The angles  $\omega, \varphi, \kappa$  cannot be derived with most of the other methods. In combination with the translation invariance the proposed method is ideal to adjust multiple cameras to each other which are positioned right in front of the DEO (e.g. to adjust multiple camera modules in cellphones to each other).

Another very positive aspect is the compact design of the setup.

Figure 4 shows the design of the prototype for a first serial product which is app. 150 x 150 x 500 mm in size.

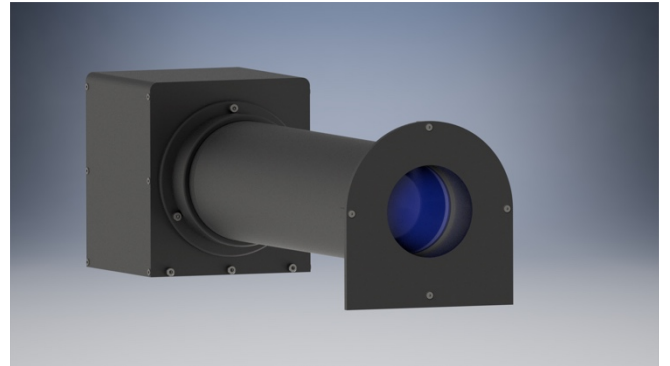


Figure 4. The current prototype.

The frequency of the grating can be adjusted to the focal length of the systems under test. For longer focal length the frequency of the grating needs to be higher in order to have enough light spots for the evaluation. We have found that even for cameras with a field of view of 125° the method creates grid points all the way into the corners. The tests on how well it works for extreme wide angles are still ongoing.

Figure 5 shows an image of a point grid generated with a camera that consists of a field of view around 125°. Figure 6 shows one from a camera with a field of view of app. 100°.

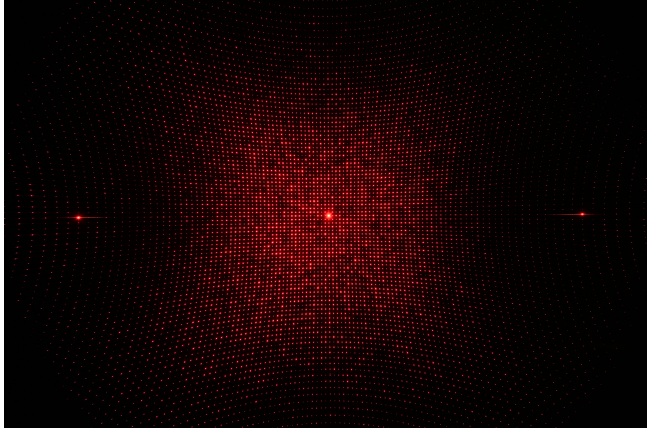


Figure 5. The grating photographed with a 125° field of view camera.

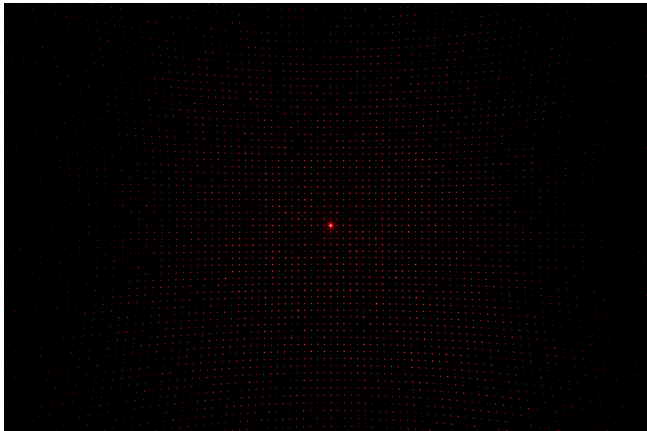


Figure 6. The grating photographed with a 100° field of view camera.

## Test results

Bauer et al. [1] describe the results they were able to achieve, which are reproduced here:

“The experiments were conducted with a Dalsa 1M28-SA which is a monochrome CMOS camera and the semiprofessional digital single-lens reflex camera Nikon D2X. Both cameras were calibrated with a wavelength of 676.4 nm, allowing a maximum diffraction angle of 59.96° needed to calibrate wide angle lenses. After aligning the DOE to the collimator system within 200 ″, the cameras are initially (#1) aligned to the DOE-system by direct lens reflections which determined the principal point at [521,481]*T* for the Dalsa and [2153,1430]*T* for the Nikon. This method allows an accuracy of about 3-4 pixel. The achieved results are given in table 3 and 4 with interior orientations ( $u_0, v_0, f$ ) stated in pixel dimensions. Exterior camera orientation ( $\omega, \varphi, \kappa$ ) and DOE tilt ( $\alpha, \beta$ ) are given in terms of the collimator coordinate frame and stated in degrees. The number of points used for calibration is denoted with  $n$ .

Table 1: Test Camera Characteristics

|              | Dalsa 1M28-SA     | Nikon D2X       |
|--------------|-------------------|-----------------|
| Pixel count  | 1024 x 1024       | 4288 x 2848     |
| Pixel size   | 10,6 mm x 10,6 mm | 5,5 mm x 5,5 mm |
| Focal Length | 4,8 mm            | 24 mm           |
| FoV          | 97°               | 99,4°           |

## Test of Dalsa 1M28-SA

Due to the low resolution of the camera and a wide-angle short-focal-length lens the  $29 \times 29$  DOE was chosen for calibration. To prove that interior- and exterior orientation parameters are independent and separable, images with different exterior orientations (dataset #2 and #3) were taken. Furthermore, the camera was calibrated with a classic photogrammetric chessboard pattern calibration. The achieved results are shown in table 2.

Table 2: Test results Dalsa 1M28-SA

|          | #1      | #2      | #3      | chessboard |
|----------|---------|---------|---------|------------|
| $n$      | 826     | 653     | 780     |            |
| $u_0$    | 521,8   | 521,9   | 521,9   | 521,3      |
| $v_0$    | 482,1   | 482,1   | 482     | 482,2      |
| $f$      | 459,6   | 459,9   | 459,9   | 460,4      |
| $k_1$    | -0,2202 | -0,2220 | -0,2223 | -0,2349    |
| $k_2$    | 0,0650  | 0,0664  | 0,0672  | 0,0826     |
| $k_3$    | -0,0094 | -0,0094 | -0,0100 | -0,0147    |
| $\alpha$ | -0,04°  | -0,07°  | -0,06°  | -          |
| $\beta$  | 0,04°   | 0,04°   | 0,01°   | -          |
| $\omega$ | 0,11°   | -3,63°  | 3,10°   | -          |
| $j$      | -0,03°  | -8,64°  | 4,95°   | -          |
| $k$      | 2,04°   | 0,04°   | 0,5°    | -          |

The standard deviation of the residuals between model- and measurement points is less than 0.2 pixel ( $< 2\mu m$ ) with a maximum error of 1 pixel for each dataset. Applying the parameters of interior orientation from one dataset to another only minimizing for exterior orientation leads to similar residuals. One major error source is the uncertainty at locating the centroid for each diffraction point in subpixel dimensions. When the projected points are rather small it is even more challenging. Additionally the distortion of the 4.8 mm wide-angle lens is very strong and the used distortion model is justified in this case.

### Test of NikonD2X

The second test series with the Nikon D2X was done in order to prove that the method also works with high resolution cameras. Here the  $71 \times 71$  DOE with a higher density of diffraction points was used. In accordance to the wavelength used for calibration only the red channel was evaluated. Starting with an aligned system (#1) and not changing the camera orientation in terms of the collimator frame, images with a tilted DOE were taken (# 2, # 3, # 4). Additionally, the exterior orientation of the camera was changed (# 5 and # 6), leaving the DOE tilted. When rotating the camera for measurement # 6, the holder of the DOE was touched by the camera lens, and from the obtained values we can derive that the DOE tilt was changed slightly during this collision. It is noticeable that an exact alignment of the DOE with respect to the incident laser beam is apparently not required for obtaining a steady calibration result. Using equation 3, both the exterior camera orientation in terms of the collimator coordinate frame and the internal camera parameters can be reproduced very well for the measurements (# 2, # 3, # 4). For all measurements (# 1...# 6), a better resolution compared to the Dalsa and therefore a more accurate subpixel position as well as a better fitting distortion model leads to better results with a standard deviation of less than 0.1 Pixels ( $< 0.4\mu m$ ) and a maximum residual of less than 0.3 pixel for each dataset."

**Table 3: Test results Nikon D2X**

|          | #1      | #2      | #3      | #4      | #5      | #6      |
|----------|---------|---------|---------|---------|---------|---------|
| n        | 1745    | 1768    | 1766    | 1706    | 1694    | 1550    |
| $u_0$    | 2149,3  | 2149,6  | 2149,7  | 2149,6  | 2149,1  | 2149,2  |
| $v_0$    | 1432,7  | 1433    | 1432,9  | 1432,6  | 1432,9  | 1432,6  |
| f        | 4261,4  | 4261,6  | 4261,5  | 4261,5  | 4261,5  | 426,7   |
| k1       | -0,0941 | -0,0945 | -0,0940 | -0,0941 | -0,0939 | -0,0938 |
| k2       | 0,0883  | 0,0897  | 0,0878  | 0,0881  | 0,0874  | 0,0871  |
| $\alpha$ | 0,02°   | 1,07°   | 0,02°   | 1,07°   | 1,07°   | 1,06°   |
| $\beta$  | -0,01°  | 0,00°   | 1,14°   | 1,12°   | 1,12°   | 1,01°   |
| $\omega$ | 0,03°   | 0,03°   | 0,03°   | 0,03°   | 1,57°   | -7,28°  |
| j        | 0,06°   | 0,06°   | 0,06°   | 0,06°   | -4,89°  | -16,75° |
| k        | 0,18°   | 0,16°   | 0,19°   | 0,19°   | 0,26°   | 0,26°   |

### Applications

The accuracy of the new technology and the advantage over conventional approaches has been shown. Now it is time to look into the fields of application. Of course, the technology can be applied to all areas that require an accurate geometric calibration.

First of all, there are 2D fields that use maps in form of images to measure distances and angles and require accurate information. Those are the classical photogrammetric applications, architecture, scientific photography, landscaping etc.

The next field are applications that require multiple cameras to either use stereo techniques or simply align cameras with multiple characteristics to each other like camera modules in cell phones, IR and visible cameras, AR and VR technologies and automotive camera modules.

Last but not least there are cameras that combine multiple technologies in a single device like the projection of structures for 3D analysis (e.g. face detection in cell phones).

### Conclusion

We have shown that the DOE based geometric calibration method only requires a single capture of the generated structure and is at least as accurate as conventional methods using the test chart-based approach. In addition, it provides the extrinsic orientation which is needed for the adjustment of cameras to a reference or to other cameras. It allows to calibrate at infinity by using a very compact design.

### Future work

A first step for future work is to increase the diameter of the DOE and the collimated light in order to be able to measure larger lenses, stereo camera pairs with a larger stereo base and increase the acceptable distance between the DOE and the device under test e.g. for automotive cameras behind windshields.

We also want to address extreme wide fields of use with this technology.

A potential next step is the exchange of the laser wavelength to calibrate systems at different wavelength.

For stereo camera pairs with a very large stereo base the cameras may need to be shifted in an accurate way which requires additional development.

And we have not tested if the grid of points generated by the DOE may allow us to utilize this method for point spread function analysis which would be extremely helpful for many modern computational photography applications.

### References

- [1] M. Bauer et al., Geometrical camera calibration with diffractive optical elements, 2008, Vol. 16, No. 25 / OPTICS EXPRESS 20241
- [2] ISO 17850 Photography — Digital cameras — Geometric distortion (GD) measurements

### Author Biography

*Dietmar Wueller studied photographic technology at the Cologne University of applied sciences. He is the founder of Image Engineering, an independent test lab that tests cameras for several photographic and computer magazines as well as for manufacturers. Over the past 20 years the company has also become one of the world's leading suppliers of camera test equipment. Dietmar Wueller is the German chair of the DIN standardization committee for photographic equipment and also active in ISO, IEC, VCX, IEEE and other standardization activities.*