Corner cases and limitations using a DOE based geometric camera calibration

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Abstract

Several years ago, the geometric calibration of cameras based on diffractive optical elements was invented, and since October 2020 the first product is commercially available.

A laser beam is expanded, and the plane wave falls onto a diffractive optical element. The DOE generates a regular grid of light dots that virtually originates from infinity.

This structure is then captured with the device under test and the dot positions are detected. From the positions, the required values can be calculated.

The potential of the method, the compactness of the setup and the ease of use have brought up many desires that so far had not been addressed.

Amongst these are:

1. *Calibration of extreme wide field of view cameras > 140°.*
2. *Calibration of cameras/lens combinations with a large entrance pupil.*
3. *Increased camera DOE distance to, e.g., measure cameras behind a windshield in automotive applications.*
4. *Camera pairs with a stereo base significantly exceeding 60 mm.*
5. *Deriving the point spread function of the system at every light dot to use the method for more than just distortion measurement, e.g., MTF determination or visualization.*

There are also a few limitations compared to the conventional methods:

- a. *Measurement at infinity only*
- b. *Stereo basis cannot be measured due to translation invariance of the method*
- c. *Determination of chromatic aberration*
- d. *Limited application of a single DOE (due to resolution of the camera and field of view)*

All these desires and limitations are discussed, and solutions are presented where possible.

DOE based geometric calibration recap

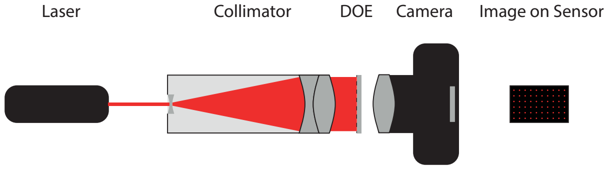


Figure 1: The principle of the DOE based geometric calibration

A laser beam is expanded, and the plane wave falls onto a diffractive optical element. The DOE generates a regular grid of light dots that virtually originates from infinity.
The camera under test is placed in front of the DOE and captures an image of the light dots. The location of the dots in the image depends on the orientation of the DOE towards the plane wave from the expanded laser, the rotation of the camera towards the incoming light, the focal length of the camera, the location of the principle point (center of distortion) and the distortion of the camera.

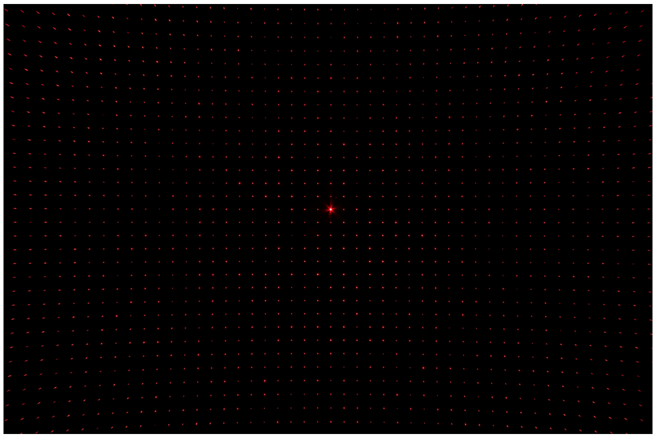


Figure 2: An example image of the captured light dots.

From these positions the following results can be calculated:

1. DOE angles to the plane wave
2. Camera rotation to the plane wave
3. Focal length f
4. Principle point u_0 and v_0
5. Distortion coefficients

Distortion models

So far, multiple distortion models exist that are used by different institutions. Based on the various discussions the authors had with the different users, most models have their origin in the two models supported by OpenCV. OpenCV is an open-source computer vision and machine learning software library [1].
The first model is the pin hole model described by:

$$x_{distorted} = x(1 + k_1r^2 + k_2r^4 + k_3r^6) + [2p_1xy + p_2(r^2 + 2x^2)] \tag{1}$$

$$y_{distorted} = x(1 + k_1r^2 + k_2r^4 + k_3r^6) + [p_1(r^2 + 2y^2) + 2p_2xy] \tag{2}$$

The part within the first brackets describes the radial part of the distortion, while the part in the square brackets describes the tangential one.

The second model is the fisheye model that describes the distortion based on the angle.
The projection coordinates are:

$$a = \frac{x}{z} \text{ and } b = \frac{y}{z} \tag{3}$$

$$r^2 = a^2 + b^2 \tag{4}$$

$$\theta = \operatorname{atan}(r) \tag{5}$$

Fisheye distortion is then defined as:

$$\theta_d = \theta(1 + k_1\theta^2 + k_2\theta^4 + k_3\theta^6 + k_4\theta^8) \tag{6}$$

The distortion point coordinates are then:

$$x' = \left(\frac{\theta_d}{r}\right) a \tag{7}$$

$$y' = \left(\frac{\theta_d}{r}\right) b \tag{8}$$

A value that describes the quality of the distortion model compared to the detected light points is the root mean square error (RMSE).

$$RMSE = \sqrt{\frac{\sum_{m=1}^{N}((x'-x)^2+(y'-y)^2}{N}} \tag{9}$$

Besides looking at the RMSE, it is also of interest to determine the maximum value and the distribution of the values over the imaging field.

DOE size-based limitations

To determine the distortion from the image center to the image corners, the light dots must cover the entire field of view of the camera. Figure 2 shows an image where the light dots fill the entire field of view. Figure 3, however, shows an image where the camera is too far from the DOE so that the corners do not show any light dots.

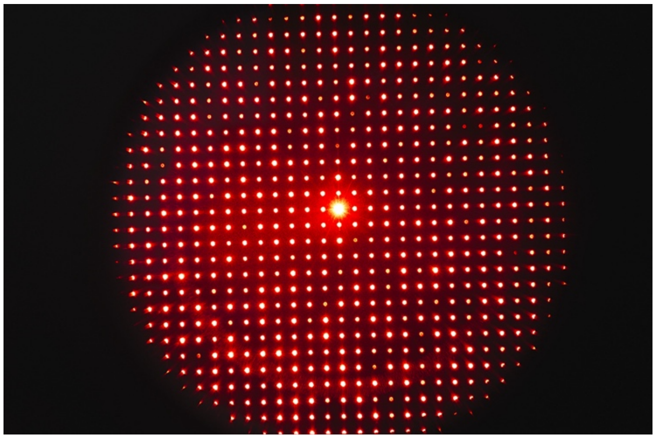


Figure 3: The captured light dots do not fill the entire field of view.

There are certain applications for the geometric calibration that require a larger DOE. For example, the calibration of an automotive camera through a windshield or a traditional DSLR camera with a large aperture lens where the front lens can have a 70 mm or 80 mm diameter. The required diameter is easy to calculate.

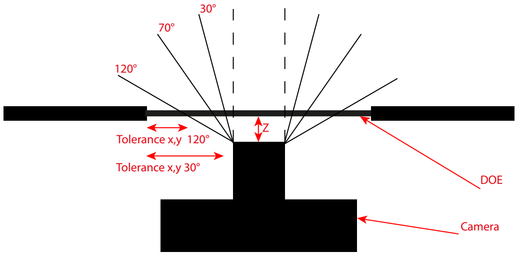


Figure 4: Geometrical requirements for camera in front of the DOE.

Table 1: Example for the geometric calculations of the camera in front of the DOE

Adjustment tolerances						
Diameter DOE	78	mm				
Diameter Front lens	18	mm				
	30	° FOV	70	° FOV	120	° FOV
Distance Z [mm]	Tolernace X	Tolerance Y	Tolernace X	Tolerance Y	Tolernace X	Tolerance Y
1	29,73	29,73	29,30	29,30	28,27	28,27
2	29,46	29,46	28,60	28,60	26,54	26,54
3	29,20	29,20	27,90	27,90	24,80	24,80
4	28,93	28,93	27,20	27,20	23,07	23,07
5	28,66	28,66	26,50	26,50	21,34	21,34
10	27,32	27,32	23,00	23,00	12,68	12,68
15	25,98	25,98	19,50	19,50	4,02	4,02
20	24,64	24,64	16,00	16,00	-4,64	-4,64
25	23,30	23,30	12,49	12,49	-13,30	-13,30
30	21,96	21,96	8,99	8,99	-21,96	-21,96
40	19,28	19,28	1,99	1,99	-39,28	-39,28
50	16,60	16,60	-5,01	-5,01	-56,60	-56,60
75	9,90	9,90	-22,52	-22,52	-99,90	-99,90
100	3,21	3,21	-40,02	-40,02	-143,21	-143,21
150	-10,19	-10,19	-75,03	-75,03	-229,81	-229,81
200	-23,59	-23,59	-110,04	-110,04	-316,41	-316,41
250	-36,99	-36,99	-145,05	-145,05	-403,01	-403,01

Adjustment tolerances						
Diameter DOE	150	mm				
Diameter Front lens	18	mm				
	30	° FOV	70	° FOV	120	° FOV
Distance Z [mm]	Tolernace X	Tolerance Y	Tolernace X	Tolerance Y	Tolernace X	Tolerance Y
1	65,73	65,73	65,30	65,30	64,27	64,27
2	65,46	65,46	64,60	64,60	62,54	62,54
3	65,20	65,20	63,90	63,90	60,80	60,80
4	64,93	64,93	63,20	63,20	59,07	59,07
5	64,66	64,66	62,50	62,50	57,34	57,34
10	63,32	63,32	59,00	59,00	48,68	48,68
15	61,98	61,98	55,50	55,50	40,02	40,02
20	60,64	60,64	52,00	52,00	31,36	31,36
25	59,30	59,30	48,49	48,49	22,70	22,70
30	57,96	57,96	44,99	44,99	14,04	14,04
40	55,28	55,28	37,99	37,99	-3,28	-3,28
50	52,60	52,60	30,99	30,99	-20,60	-20,60
75	45,90	45,90	13,48	13,48	-63,90	-63,90
100	39,21	39,21	-4,02	-4,02	-107,21	-107,21
150	25,81	25,81	-39,03	-39,03	-193,81	-193,81
200	12,41	12,41	-74,04	-74,04	-280,41	-280,41
250	-0,99	-0,99	-109,05	-109,05	-367,01	-367,01

Table 1 is simply calculated from the geometric conditions described in figure 4. The further the camera is away from the DOE the more accurately it needs to be positioned. These conditions are calculated using the diameter of the DOE, the diameter of the front lens and the angle of the field of view of the camera. The numbers in red indicate that it is not possible to fill the whole field of view with light dots. If the size of the DOE increases the possible distance will increase as well.

Calibrating cameras through windshields

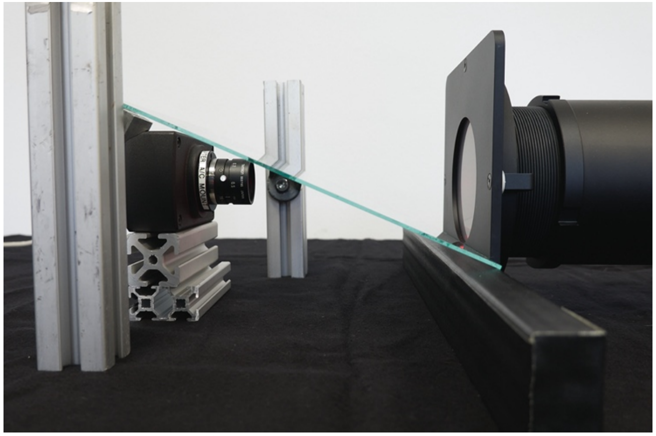


Figure 5: Principle setup for geometrical calibration through windshields.

Windshields are typically not made of optical glass and two major variations can be observed when analyzing the glass.

1. Variations in thickness of the glass over the field (planarity).

2. Varying refraction index over the field due to the tempering of the glass.

A simulation with a standard plane glass shows that the position of the light dots shifts slightly due to the optical path difference (see figure 6).

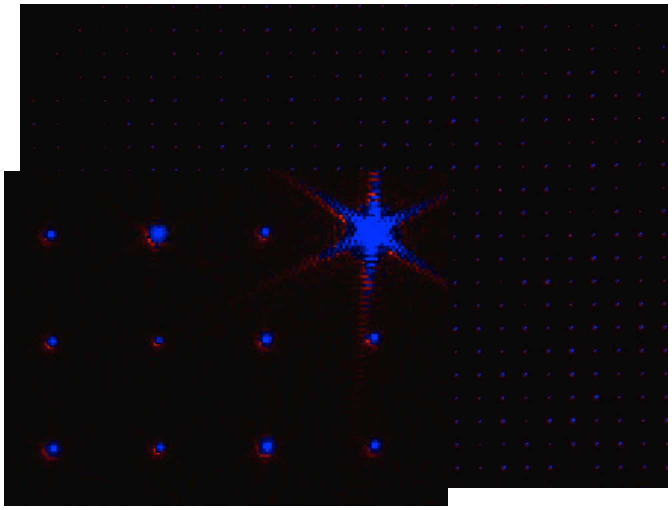


Figure 6: A plane optical glass simply shifts the dot positions.

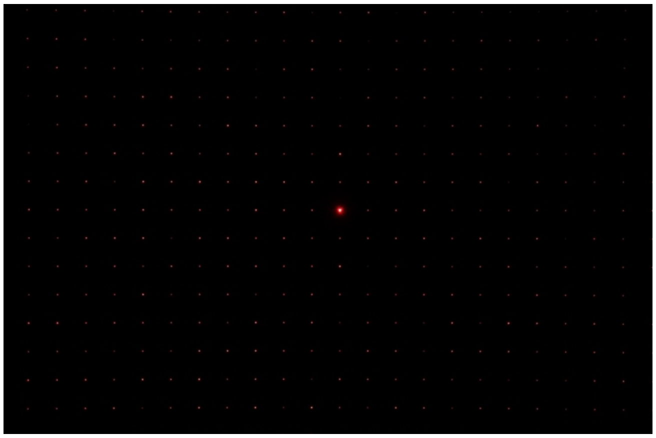


Figure 7: Windshield glass with good optical quality does not show a significant variation of the light dots except a position shift.

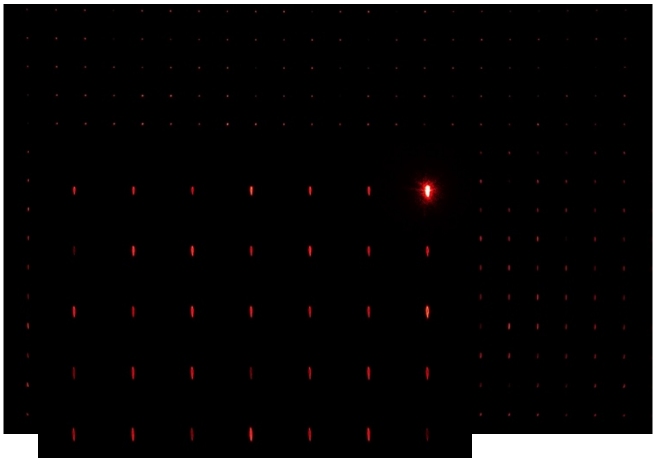


Figure 8: A bad optical glass with varying refraction index changes the dot size and form.

Good and bad samples were prepared for this test and provided for evaluation by AGP Europe GmbH.

Calibrating extreme wide angles

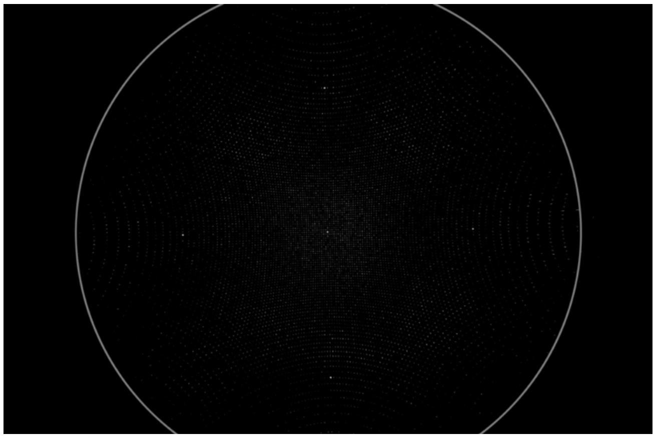
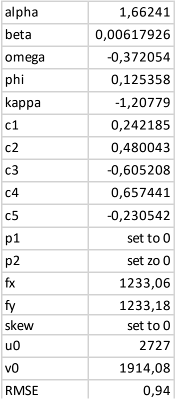


Figure 9: Calibrating a camera with a fisheye lens is possible using a DOE based device. The grey circle indicates the field of view of the camera.

Table 2: The calibration results of a sample camera with a fisheye lens.



alpha	1,66241
beta	0,00617926
omega	-0,372054
phi	0,125358
kappa	-1,20779
c1	0,242185
c2	0,480043
c3	-0,605208
c4	0,657441
c5	-0,230542
p1	set to 0
p2	set zo 0
fx	1233,06
fy	1233,18
skew	set to 0
u0	2727
v0	1914,08
RMSE	0,94

A higher RMSE value for a fisheye lens is expected.

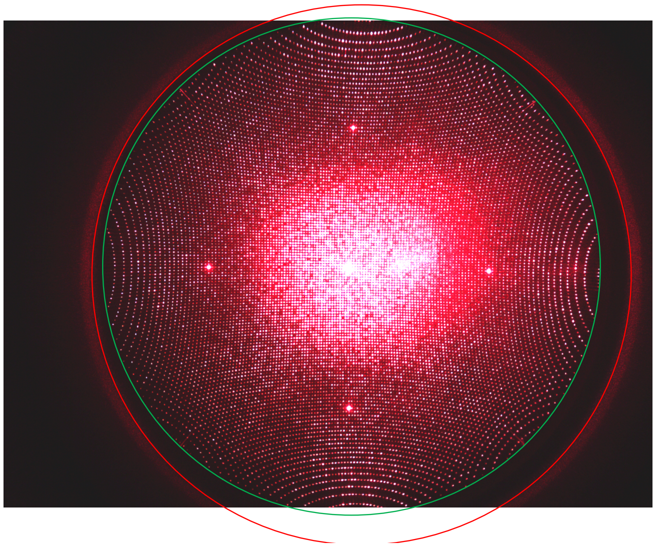


Figure 10: The (overexposed by intention) image shows a 180° field of view camera.

Our first tests show that it is possible to even calibrate cameras with fisheye lenses using a DOE. We receive meaningful values and, while the RMSE value is slightly higher, it still seems to be acceptable. In figure 10 the green circle shows the limit of the DOE captured with a 180° field of view camera with an imaging circle that is indicated in red.

Wavelength variation

In order to get high-quality, sharp light dots, the light source needs to be monochromatic, and the smaller the spectral band is, the smaller the light dots will be. The easiest way to handle monochromatic light source is a frequency stabilized single mode laser diode.

We have looked into multimode lasers and figure 11 shows the resulting light dots with this source. So, even a multimode laser diode is not suitable for the application.

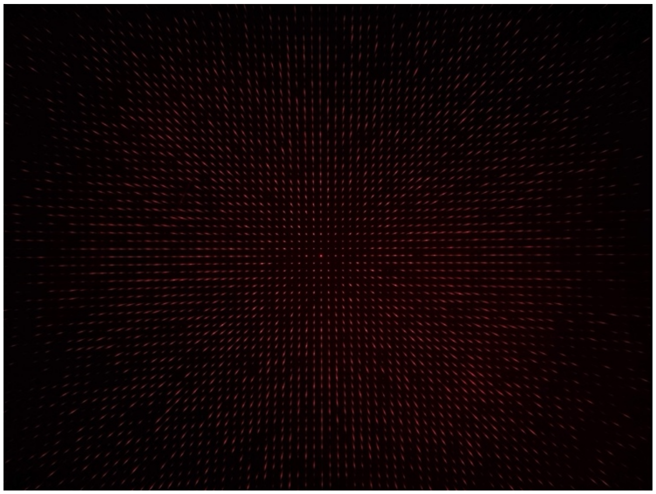


Figure 11: The use of a multimode laser for illuminating the DOE.

In addition, people asked about illuminations at another wavelength. In principle, any monomode laser can be used at any wavelength for which the DOE material works. However, the DOE that gets used in our case has been optimized for 633 nm and the frequency stabilized laser diodes at the required low power are hard to find at a shorter wavelength than that. On the other hand, constructing a specialized version in the near IR should be possible.

Calibrating cellphone zoom

Due to the form factor of a cellphone, the zoom capabilities are usually achieved by combining multiple camera modules with different focal lengths.

The calibration results, including the outer orientation with the three camera angles for pitch, yaw, and roll, provide all necessary information to perfectly align the cameras to each other. Once the images are undistorted and the camera angles have either been adjusted on the production line (extrinsic calibration) using the DOE-based device or compensated in the image processing, the morphing between the cameras should be easy.

However, a typical shift in the image due to an improper calibration may not directly be visible in a video of the DOE-based structure because of the translational invariance of the diffraction structure.

References

[1] OpenCV, https://opencv.org

[2] Wueller Dietmar, A new dimension in geometric camera calibration, Electronic Imaging, Image Quality and System Performance XVII, pp. 18-1-18-5(5)

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.