A New Dimension in Geometric Camera Calibration

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Goals

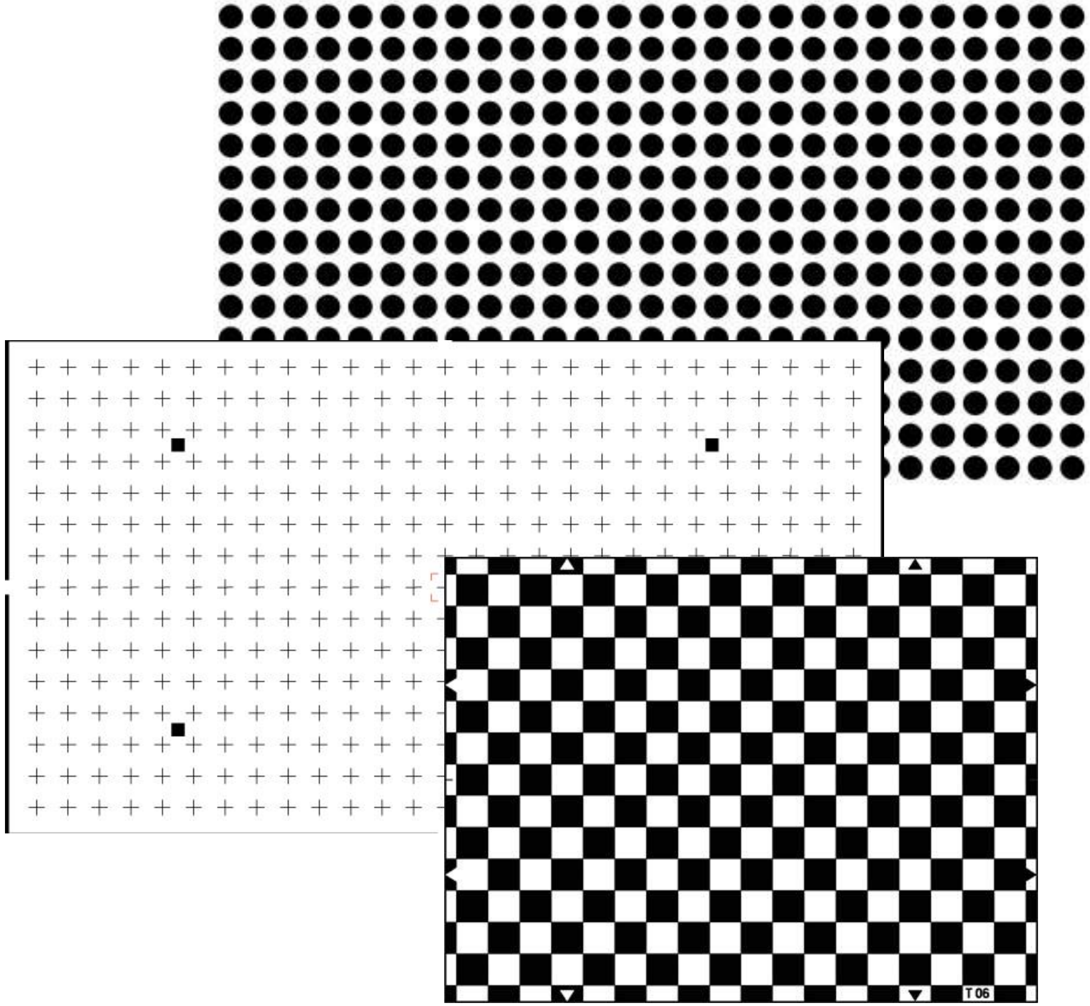
Geometric camera calibration is essential

- To measure distance in images
- To detect objects in images
- To compensate for high distortion levels
  especially for wide field-of-view cameras
- To accurately align stereo camera pairs

Current methods

Current methods for geometric calibration

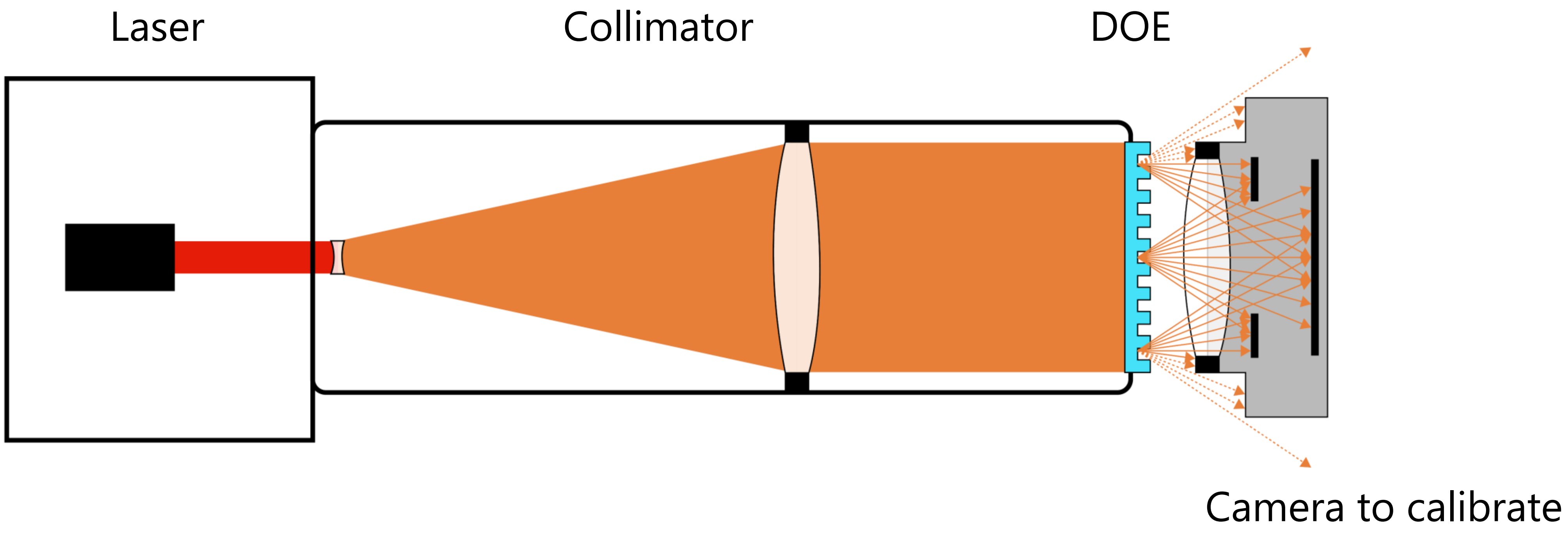
- Regular patterns to determine distortion over the imaging field
- Test chart based methods
- Large charts required for wide field-of-view cameras
- Relay lenses required for compact methods and solutions for measurements at infinity
    - Relay lenses introduce distortion and need to be characterized



These methods allow for distortion measurement and inner orientation but not outer orientation

The new approach

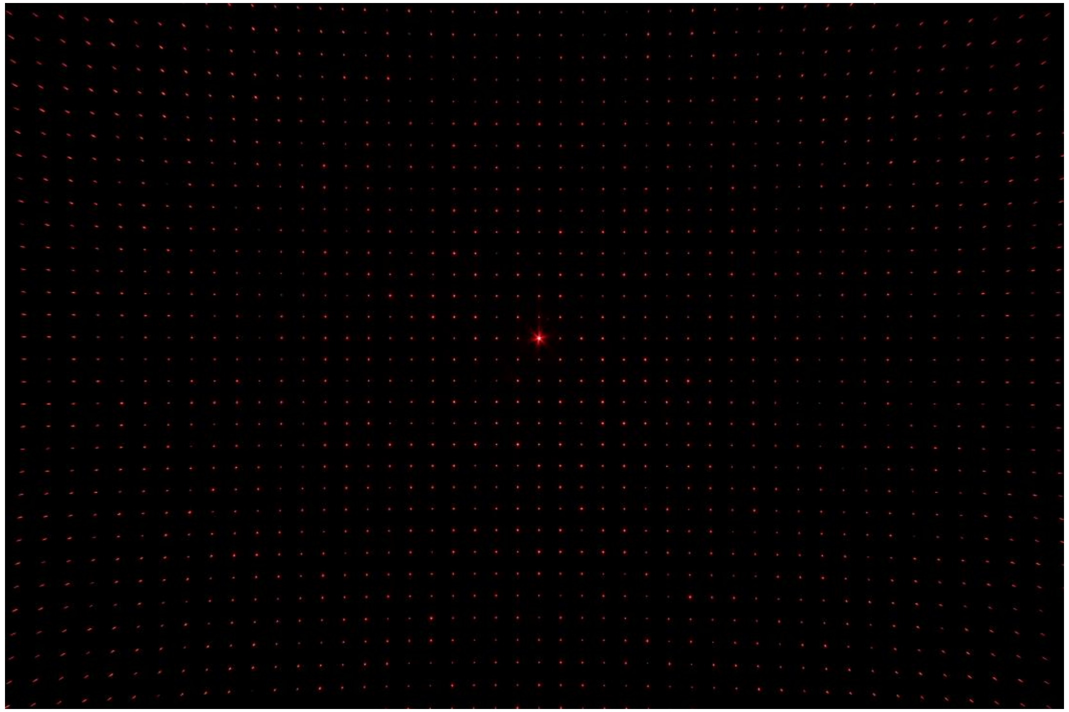
A beam expanded laser in combination with a diffractive optical element (DOE)



The new approach

Characteristics

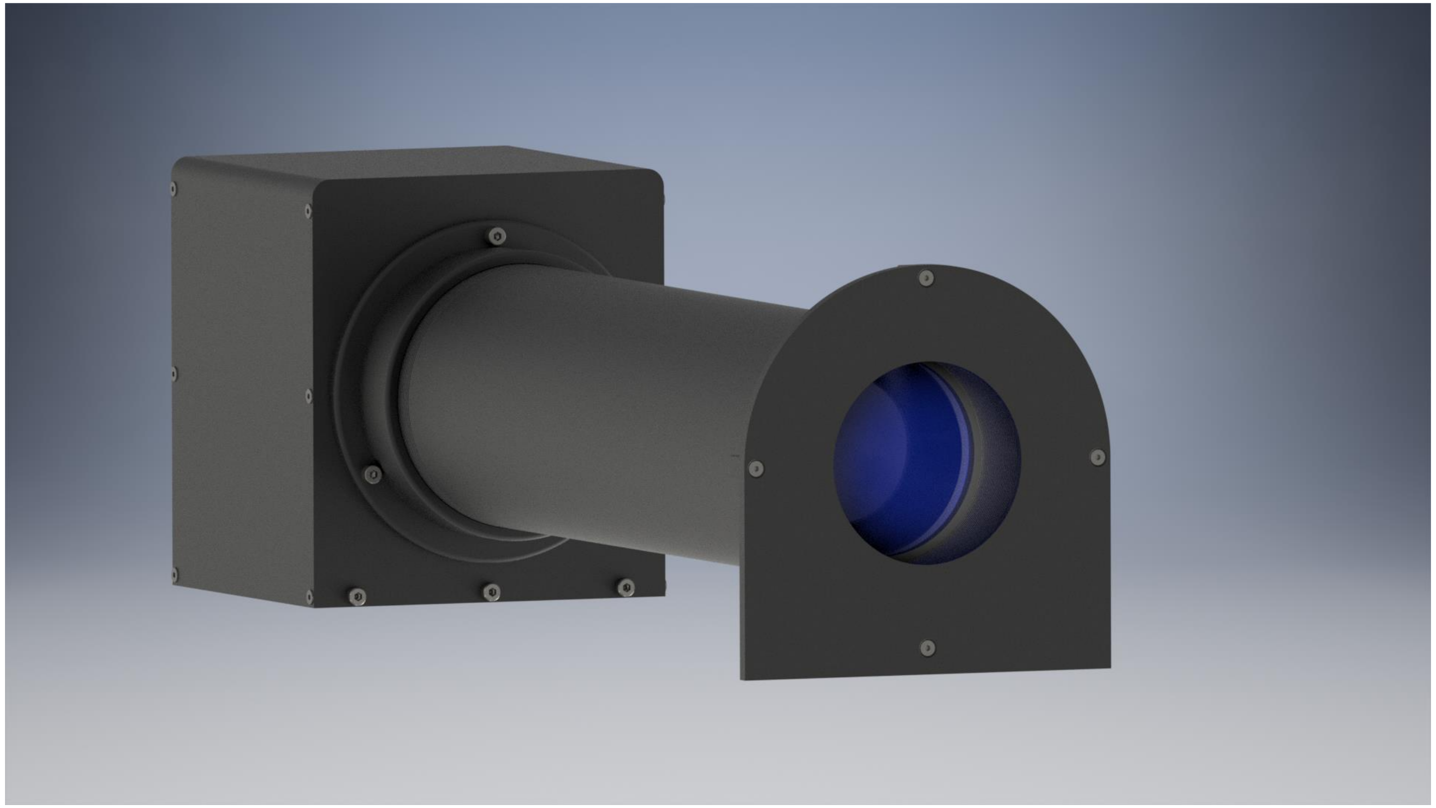
- Generating a regular grid of light spots originating from infinity
- Camera position is translation insensitive (to a certain extent)
- Easily manage the angle of camera rotation
- No relay lens required
- Very compact design
- Calibrate large field-of-view cameras
- Stereo camera adjustments



The new approach

The prototype

The beam diameter is currently 75 mm



The new approach

Background information:

The grating with its point grid from infinity is described by the following formula:

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

with r describing the rotation of the DOE in relation to the expanded plane wave of the laser

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

and F being the frequency of the grating and λ being the wavelength of the laser

The new approach

Background information:

The beam direction into the camera coordinate frame depends on the exterior orientation of the camera and as a result, the grating formula needs to be adjusted:

$$d' = \begin{bmatrix} R & t \\ 0 & 1 \end{bmatrix} d$$

with R being a 3x3 camera rotation matrix and *t* being the translation of the camera

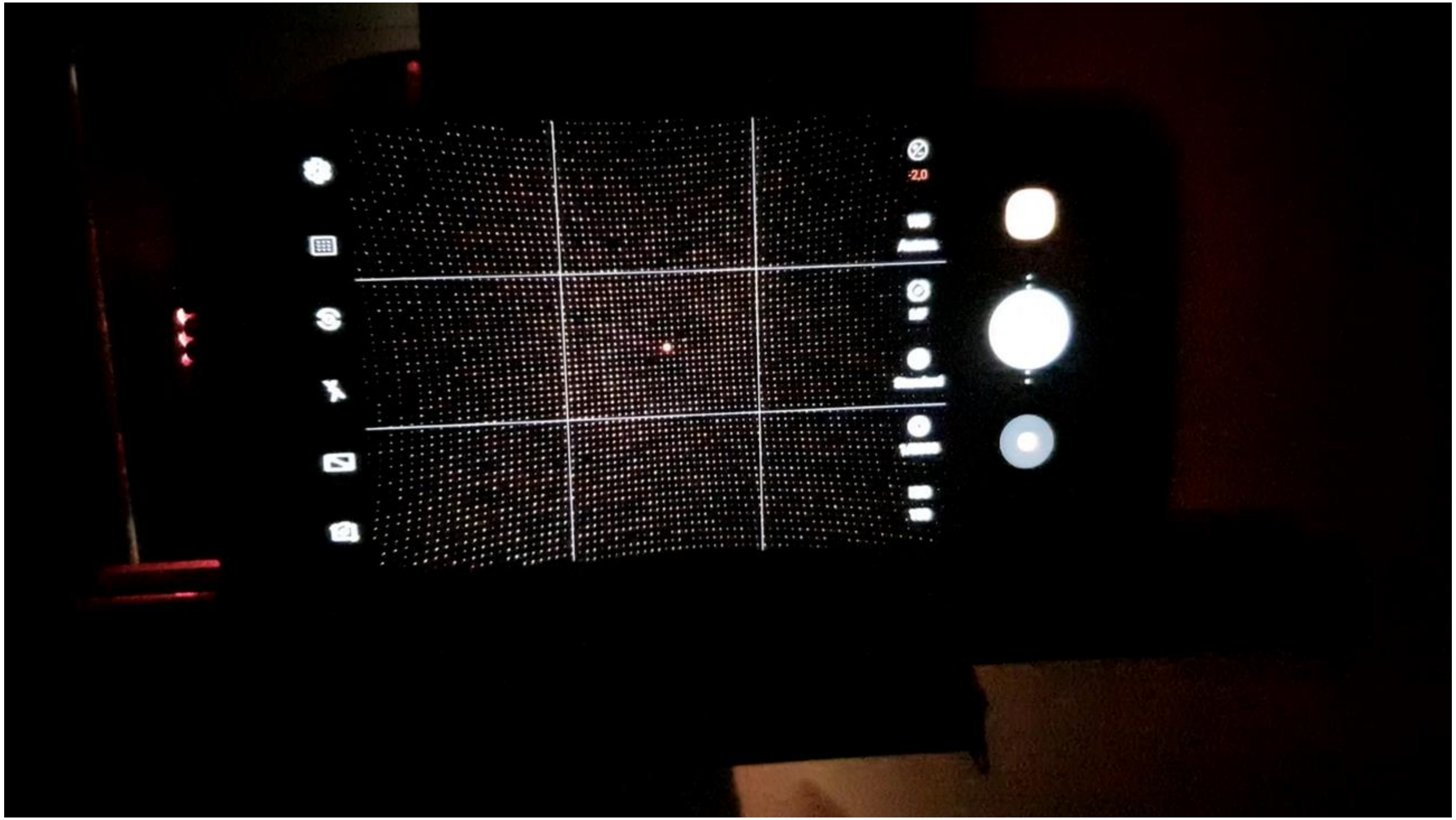
This information shows that the mapping of ideal points is invariant of the translation.

The new approach

Translation independent

The new approach

Rotation angles are part of the desired output when evaluating the alignment of cameras.



The new approach

Background information

The image created by the camera is a projection of the 3D image into the 2D space of the image:

- $$\begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} X/Z \\ Y/Z \\ 1 \end{bmatrix}$$

with Z being the projection plane Z = 1

The new approach

Background information

For the image in pixel coordinates the camera matrix comes into play:

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \mathrm{K} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

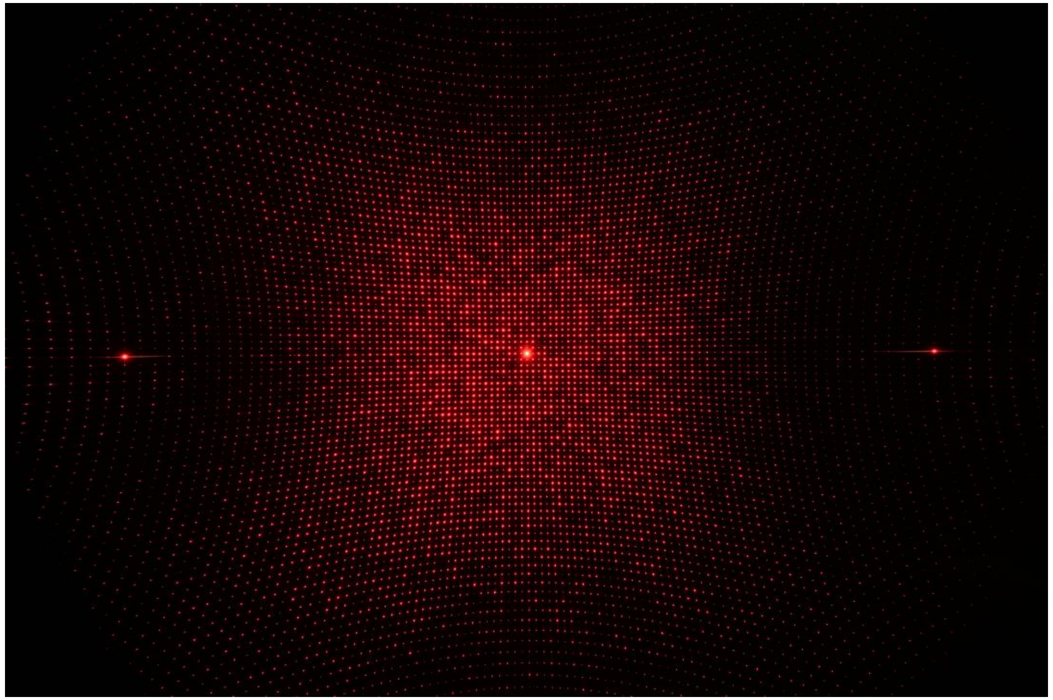
with

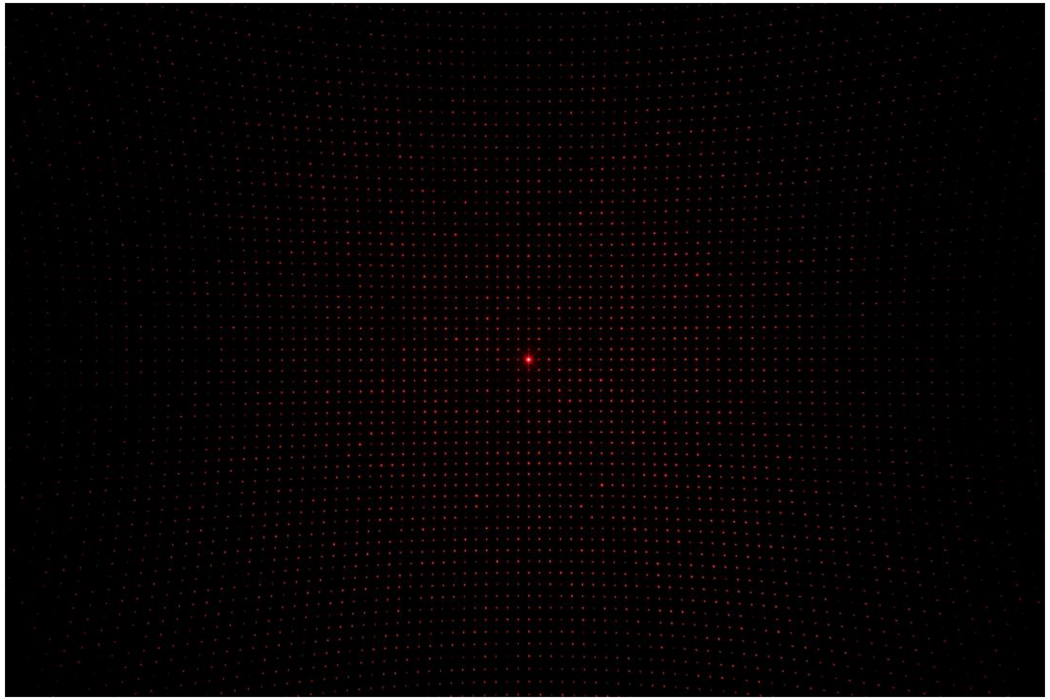
$$K = \begin{bmatrix} f & 0 & u_0 \\ 0 & f & v_0 \\ 0 & 0 & 1 \end{bmatrix}$$

with *f* being the focal length of the camera and u_0 and v_0 being the principal point. Now *u* and *v* are the ideal coordinates.

The new approach

The impact of focal length / field-of-view on the point grid





The smaller the field-of-view the fewer available dots (measuring points). If there are too few dots, the DOE has to be exchanged. The max. field of view used is app. 125°.

The new approach

Background information

Once we add the distortion model, we end up with:

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

with r = $x^2 + y^2$

The new approach

Background information

We can now calculate all necessary values for the geometric calibration:

- 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 α and β
- The camera angles in relation to the incident expanded plane laser beam ϖ, φ, κ

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