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OpenCSP Camera Calibration

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ABSTRACT

This report provides instructions on how to perform an OpenCSP camera lens calibration, which characterizes the inherent distortion in camera-lens systems. This calibration is necessary for many OpenCSP photogrammetry calculations and should be performed individually for every new camera or after adjusting lens settings.

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ACRONYMS AND TERMS

Acronym/Term	Definition
OpenCSP	Open-source python library for concentrating solar power applications
OpenCV	Open Computer Vision
GUI	Graphical user interface

1. INTRODUCTION

Camera-lens pairs inherently induce optical distortion into imaging systems. Camera calibrations are performed to model this distortion and account for it. OpenCSP uses the OpenCV lens distortion model [1] where a camera is modeled as an ideal pinhole camera and lens distortion is fit to a two-dimensional polynomial function. Thus, the camera is represented as a series of coefficients. Section 4 contains a technical description of this model.

2. REQUIREMENTS

The physical camera with lens attached that is to be calibrated. Sandia has successfully used Basler acA1600-20gm and acA1600-60gc cameras with C-mount lenses (example: Fujinon HF25SA-1, F/1.4, 25mm). Zoom lenses may be more difficult to calibrate; prime lenses with a single focal length are preferred.

Ensure frames can be captured by the camera. If using a Basler camera, the analysis computer needs a network adapter card that can support a GigE camera.

A target with black and white checkerboards. Sandia uses a checkerboard with 22x19 squares; each square has a 50mm side length. The checkerboard must be very flat and rigid; the Sandia checkerboard flatness error does not exceed ± 0.5 mm peak to valley.

OpenCSP must be installed on the analysis computer and all unit tests must run successfully. See the OpenCSP setup instructions for more information [2].

The user needs a way of mounting or holding the checkerboard steady and without warping it. The checkerboard needs to remain flat through the entire calibration process.

3. PROCEDURE

1. Securely fasten the lens to the camera body. Any lens movement or adjustment of the lens focus or zoom will change the calibration parameters.
2. Capture images of the checkerboard with the camera/lens assembly. Example images are shown in Appendix A.
 - Hold the checkerboard steady in a fixed location. Make sure not to warp the checkerboard; the checkerboard must remain flat.
 - Capture about 50 images; you cannot capture too many.
 - If possible, capture about half with the checkerboard horizontal, and half with the checkerboard vertical to average out errors in the checkerboard squares.
 - Each image should contain the entire checkerboard.
 - Watch for glare, dark spots, shadows, motion blur, etc.
 - Try to fill as much of the image with the checkerboard as possible.
 - **Important:** Present the checkerboard to the camera at angles between 30° and 45° . This is important for an accurate focal length calculation. I.e., angle θ in Figure 1 should always be between 30° and 45° . This causes perspective foreshortening in the image, which is needed to remove numerical ambiguity in focal length estimation.

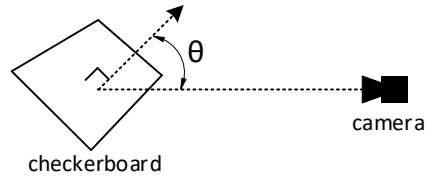


Figure 1: Checkerboard-camera angle

Solve for camera calibration parameters and save Camera file. We recommend using the OpenCSP CameraCalibration GUI (graphical user interface). If desired, the user can perform a camera calibration using third-party software and manually import the parameters into the OpenCSP Camera class if the distortion model matches the description in section 4. Instructions for using OpenCSP’s CameraCalibration GUI are detailed below in section 3.1.

3.1. Using the OpenCSP Camera Calibration GUI

1. Run the camera calibration graphical user interface:

```
>> python.exe opencsp/app/camera_calibration/CameraCalibration.py
```

The window shown in Figure 2 will appear. Buttons are ordered top to bottom in the order which they should be used. Buttons will be grayed-out if they cannot yet be used.

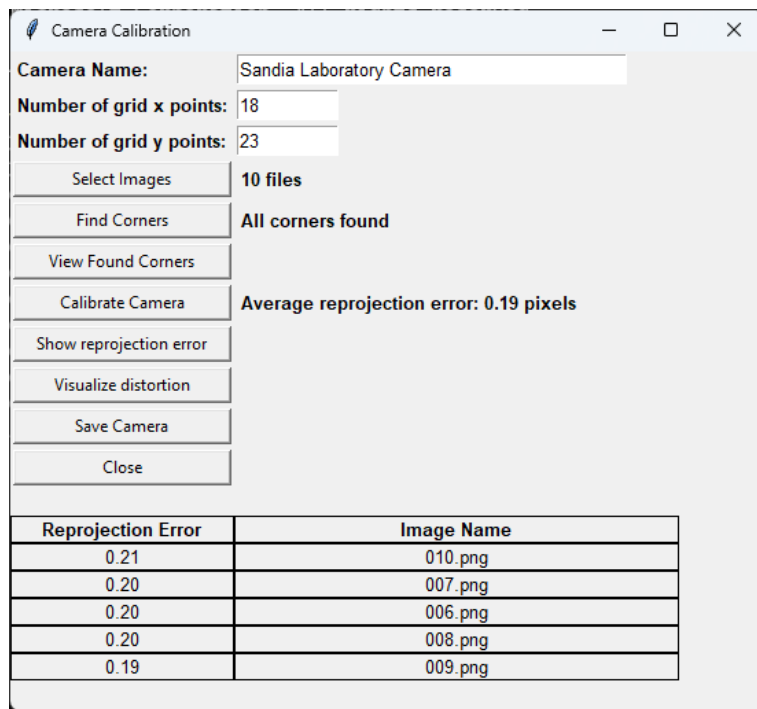


Figure 2: Camera Calibration User Interface

2. Input a camera name and the number of x and y calibration grid points. A *grid point* is a corner surrounded by two black, and two white squares. (i.e. one less than the number of total squares in the x or y direction)

3. Click *Select Images* and navigate to the captured camera images.
4. Click Find Corners.
5. If desired, click *View Found Corners* and review the found corners to make sure corners were found properly.
6. Click Calibrate Camera.
7. We recommend clicking *Show reprojection error* or *Visualize distortion* to show the RMS reprojection errors per image or the image distortion visualizations. See Appendix A.
8. The five images with the highest reprojection error are shown in the bottom table. If desired, these images can be removed and the analysis repeated.
9. Click *Save Camera* to save the camera parameters in an HDF5 file.

4. CAMERA MODEL TECHNICAL DESCRIPTION

The OpenCSP camera calibration app uses the OpenCV `calibrateCamera()` function; the outputs are described below [1]. For camera-lens assemblies with low amounts of distortion, the four-coefficient model, $[k_1, k_2, p_1, p_2]$, is likely sufficient [3]. For wide-angle lenses the five-coefficient model, $[k_1, k_2, p_1, p_2, k_3]$, may be necessary [3]. Sandia has historically not used wide-angle of fisheye lenses with SOFAST; thus, the OpenCSP CameraCalibration GUI only calculates the four-coefficient model. However, the OpenCSP Camera class is compatible with higher order distortion models if instantiated manually.

Here we compute the image coordinate (u, v) given a real-world point (X_c, Y_c, Z_c) and a camera model $[k_1, k_2, p_1, p_2, k_3]$.

Let us define the (x, y, z) location of a point in the field of view of the camera as (X_c, Y_c, Z_c) . These points are relative to the camera coordinate system origin.

For an ideal pinhole camera model, the ideal normalized camera coordinates (x', y') are:

$$\begin{aligned} x' &= \frac{X_c}{Z_c} \\ y' &= \frac{Y_c}{Z_c} \end{aligned} \tag{Equation 1}$$

The distorted normalized camera coordinates are denoted as x'' and y'' . The four-coefficient model uses coefficients $[k_1, k_2, p_1, p_2]$ and $k_3 = 0$. The five-coefficient model uses coefficients $[k_1, k_2, p_1, p_2, k_3]$. Higher order distortion models are supported by the OpenCSP Camera class but are not described here.

$$\begin{aligned} x'' &= x'(1 + k_1 r^2 + k_2 r^4 + k_3 r^6) + [2p_1 x' y' + p_2 (r^2 + 2x'^2)] \\ y'' &= y'(1 + k_1 r^2 + k_2 r^4 + k_3 r^6) + [p_1 (r^2 + 2y'^2) + 2p_2 x' y'] \end{aligned} \tag{Equation 2}$$

where $r^2 = x'^2 + y'^2$.

The pixel location of the image, (u, v) of the point, (X_c, Y_c, Z_c) , on the camera's sensor is given by the matrix operation below:

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x'' \\ y'' \\ 1 \end{bmatrix} \quad \text{Equation 3}$$

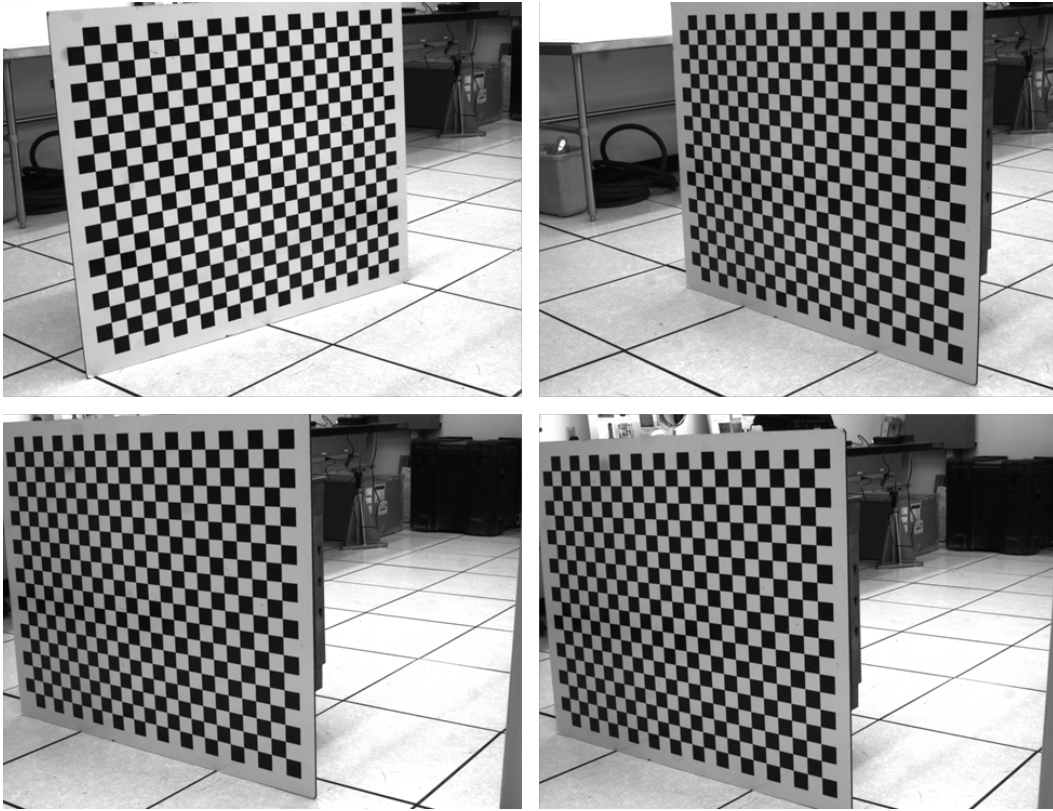
Where:

- f_x and f_y are the x/y focal lengths in units of number of x/y pixel dimensions.
- c_x and c_y are the location of the center of the image (the optical axis) relative to the upper-left corner of the camera sensor. The center of the upper-left corner pixel has (u, v) coordinate $(0, 0)$.

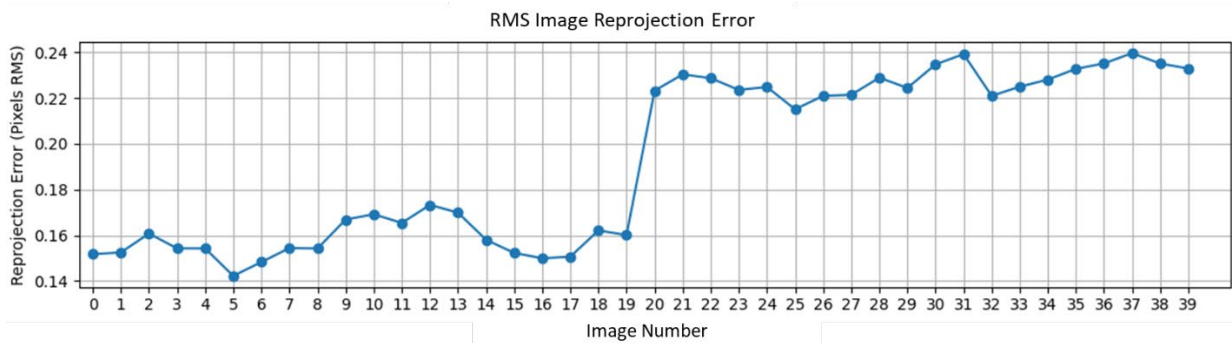
Since the distortion parameters operate on normalized camera coordinates, $[k1, k2, p1, p2, k3]$ are intrinsic to the camera-lens assembly. However, the camera terms, $[f_x, f_y, c_x, c_y]$ are dependent on the pixel dimensions. If the image resolution decreases while maintaining the same sensor size (for example, if the image is downsampled to half the original resolution), the intrinsic distortion coefficients will remain the same while the f and c terms will scale.

APPENDIX A. EXAMPLE SANDIA CAMERA CALIBRATION RESULTS

1. Example checkerboard images



2. RMS reprojection error versus image number

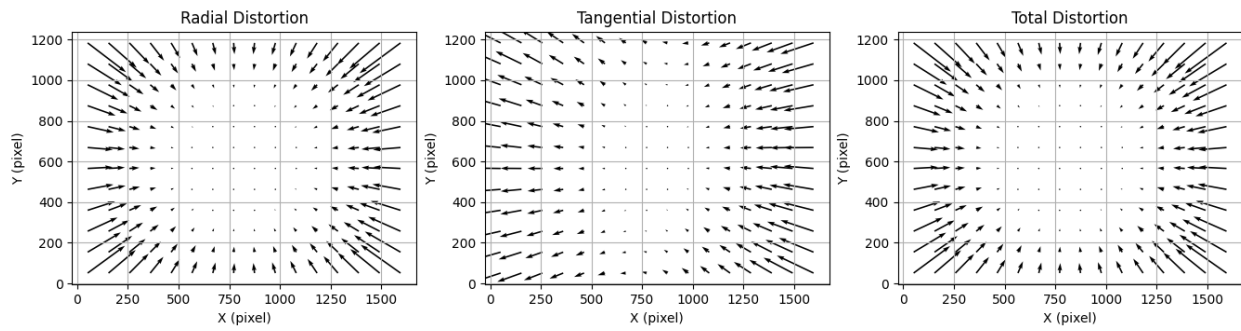


Reprojection error is computed by applying the camera model to the input images to compute expected image positions, and comparing the resulting projected image locations against actual image locations. This discrepancy is reprojection error.

The jump in values seen in the above plot are due to changing the calibration target incidence angle from +45deg to -45deg. This is often seen.

Reprojection errors exceeding 1.0 pixels is an indication of a poor calibration. If encountered, discard images with high reprojection error, capture new images to replace them, and repeat the calibration process.

3. Radial, tangential, and total distortion visualization



The radial distortion plot indicates that this lens produces barrel distortion.

REFERENCES

- [1] OpenCV Camera Calibration and 3D Reconstruction, https://docs.opencv.org/4.x/d9/d0c/group_calib3d.html.
- [2] OpenCSP Team. OpenCSP Getting Started Guide. <https://opencsp.readthedocs.io/en/latest/contributing.html#getting-started>.
- [3] What Is Camera Calibration, <https://www.mathworks.com/help/vision/ug/camera-calibration.html>.

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