

# Computer Vision

## Camera calibration

### Objective:

In this exercise you will learn how to calibrate a camera. The camera calibration computes the intrinsic parameters of a camera and estimates the distortion coefficients of the lens. Two algorithms will be implemented: the simple Direct Linear Transform (DLT) algorithm and the Gold Standard algorithm.

As a preparatory step you have to make at least one image of a 3D calibration object. An example is shown in Figure 1. Make sure that the object fills almost the whole image. The closer the checkerboard patterns are to the image borders, the more precise the calibration and especially the radial distortion can be estimated. For your convenience, we provide the original image of Figure 1 in the attachment. You can use it directly for your implementation and report.

To run the calibration you need the image coordinates and the 3D coordinates of the calibration object corners. To get the 3D coordinates you can simply assign the origin of the coordinate system somewhere on the calibration object (as shown in Figure 1). The code framework provides a function for clicking the point correspondences. For each clicked image point you have to enter the 3D-coordinate.

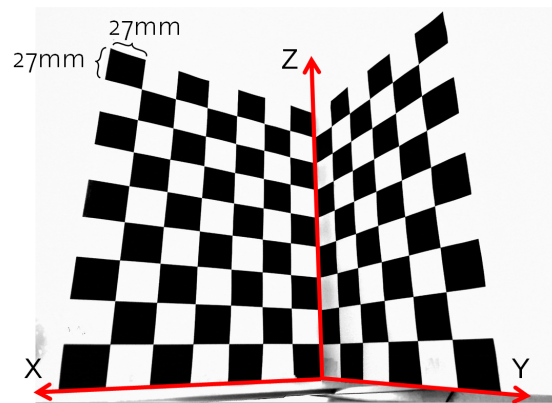


Figure 1: Typical calibration object.

## 2.1 Data Normalization (20%)

Data normalization is an essential part of the DLT algorithm. First, for all points, scale the homogeneous vectors such that the last entry becomes 1, i.e.,  $x = (x, y, 1)^T$  and  $X = (x, y, z, 1)^T$ .

Then, transform the input points so that the centroid of the points is at the origin and that the average Euclidean distance from the origin is  $\sqrt{2}$  for the image points, and  $\sqrt{3}$  for the object points. The distance to the origin should not contain the last value of the homogeneous coordinate, so for instance, the distance to the origin for image points is  $\sqrt{x^2 + y^2}$ . Find transformations matrices  $T$  and  $U$  such that the normalized image points are  $\hat{x}_i = Tx_i$  and the normalized object points are  $\hat{X}_i = UX_i$ . Make sure the last entries remain as 1.

## 2.2 Direct Linear Transform (40%)

Implement the DLT algorithm to estimate the camera matrix from the given point correspondences. The goal of the DLT is to minimize the algebraic error of the linear system of our camera model.

- Compute the normalized camera matrix  $\hat{P}$  with the DLT algorithm:

Each correspondence  $\hat{X}_i \leftrightarrow \hat{x}_i$  is inserted to the equation

$$\begin{bmatrix} w_i \hat{X}_i^\top & \mathbf{0}^\top & -x_i \hat{X}_i \\ \mathbf{0}^\top & -w_i \hat{X}_i^\top & y_i \hat{X}_i \end{bmatrix} \begin{pmatrix} \hat{P}^1 \\ \hat{P}^2 \\ \hat{P}^3 \end{pmatrix} = 0 \quad (1)$$

where  $\hat{P}^i$  are the row vectors of  $\hat{P}$ .

Stacking the equations for all point correspondences (i.e., 6 correspondences for DLT algorithm) results in a  $12 \times 12$  matrix  $A$  where  $AP = \mathbf{0}$ . The solution for  $P$  is the right null-vector of  $A$  that can be computed with the singular value decomposition of  $A$ .

- Compute the denormalized camera matrix  $P = T^{-1} \hat{P} U$  using the matrices from last section.
- Factorize the camera matrix into the intrinsic camera matrix  $K$ , a rotation matrix  $R$  and the camera center  $C$ .

$$P = [M | -MC] = K[R | -RC] \quad (2)$$

where  $M = KR$  is the product of the intrinsic matrix and the camera orientation rotation matrix and  $C$  is the camera center. The matrix  $M$  can be decomposed with a RQ-decomposition. The camera center  $C$  is the point for which  $PC = \mathbf{0}$ . Which means that it corresponds to the the right null-vector that can be obtained from the SVD of  $P$ .

- Visualize the reprojected points of all checkerboard corners on the calibration object with the computed camera matrix.
- What happens if you use the unnormalized points?



### 2.3 Gold Standard algorithm (40%)

The Gold Standard algorithm minimizes the geometric error  $\sum_i d(x_i, \hat{x}_i)^2$  where  $x_i$  is the measured (clicked) point and  $\hat{x}_i$  is the projected object point  $PX_i$ . Here  $d(x_i, \hat{x}_i)$  is the Euclidean distance between  $x_i$  and  $\hat{x}_i$ .

- Normalize the input points and run the DLT algorithm to get an initial camera matrix  $\tilde{P}$  for the optimization.
- Visualize the hand-clicked points and the reprojection of the points on the calibration object obtained by using the computed camera matrix.
- Refine the estimated camera matrix  $\tilde{P}$  by minimizing  $\sum_i d(x_i, \hat{x}_i)^2$ . The cost function can be minimized with *fminsearch* from MATLAB. For Gold Standard algorithm, you can use more than 6 points to get more accurate results.
- Denormalize and factorize the camera matrix as in task 2.2
- Compute the mean reprojection-error, i.e.,  $\frac{1}{N} \sum_{i=0}^{N-1} d(x_i, PX_i)$  of used point correspondences.
- Visualize the reprojected points of all checkerboard corners on the calibration object with the computed camera matrix.

### 2.4 Bouget's Calibration Toolbox

This task will not be graded. If you have interests, you can try to calibrate your own camera with a standard toolbox provided by MATLAB. Details on how to use it can be found from [1]. You need to print out a calibration pattern and make several images of it.

#### Hand in:

Write a short report explaining the main steps of your implementation and discussing the results of the methods. The report should contain images showing the clicked 2D points before calibration and the the reprojected 3D points using the calibration parameters. Send the report together with your source code to moodle.

#### References:

[1] <https://nl.mathworks.com/help/vision/ug/single-camera-calibrator-app.html>