BONN-RHEIN-SIEG UNIVERSITY OF APPLIED SCIENCES

Scientific Experimentation and Evaluation - Assignment 05 - Camera Calibration

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CONTENTS

1 ABSTRACT

This report describes the design and the process of the camera calibration and discusses the resulting problems and parameters.

2 SETUP

The chessboard pattern has been fixed on a solid plain ground. The camera has been held in hands and images have been taken from different angles w.r.t. the chessboard. In the online tutorial ([2]) 20 images were sufficient, so we used 27 images to be on the safe side (see figure 2.1). The orientations of the images differ for each image and provide a good range of different orientations.

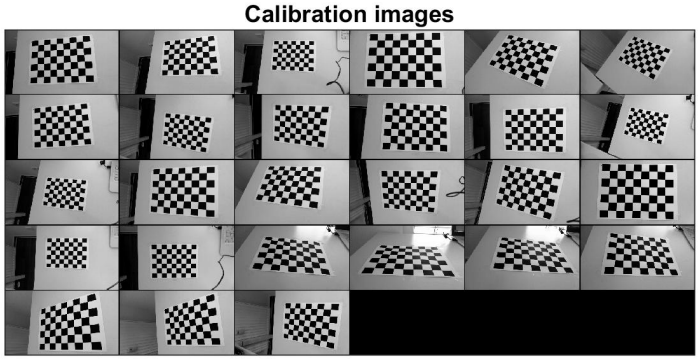

Figure 2.1: Calibration Images

3 DESCRIPTION CAMERA PARAMETERS

Matlab computes the following parameters:

- **Focal Length** (2x1 vector)
  "The focal length of an optical system is a measure of how strongly the system converges or diverges light." [3] (see figure 3.1).
- **Principal Point** (2x1 vector)
  "The principal points are the points where the principal planes cross the optical axis."[3]

"The two **principal planes** have the property that a ray emerging from the lens appears to have crossed the rear principal plane at the same distance from the axis that that ray appeared to cross the front principal plane, as viewed from the front of the lens. This means that the lens can be treated as if all of the refraction happened at the principal planes."[3] (see figure 3.2).

- **Skew Coefficient** (scalar)
  "The skew coefficient defines the angle between the x and y pixel axes"[1]

- **Distortions** (5x1 vector)
  Matlab stores both radial and tangential distortions in the distortions vector.[1]
  Radial distortions increase or decrease magnification with the distance to the optical axis[3](see figure 3.4).
  Tangential distortion occurs when camera lens and sensor are not parallel (see figure 3.3).

- **Rotations** (set of 3x3 rotation matrices)
  Rotations from images into reference frame.[1]

- **Translations** (set of 3x1 vectors)
  Coordinate vectors of the origin of the grid pattern in camera reference frame. [1]

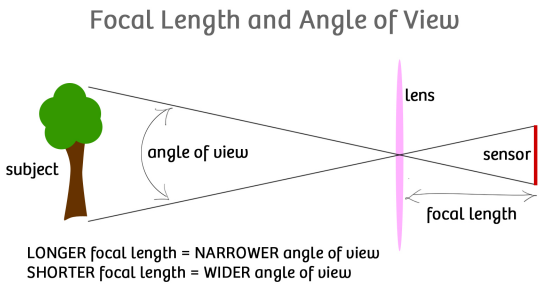

Figure 3.1: Focal Length,
http://static.snapsnapsnap.photos/wp-content/uploads/2014/11/Focal-Length-and-Angle-of-View.jpg

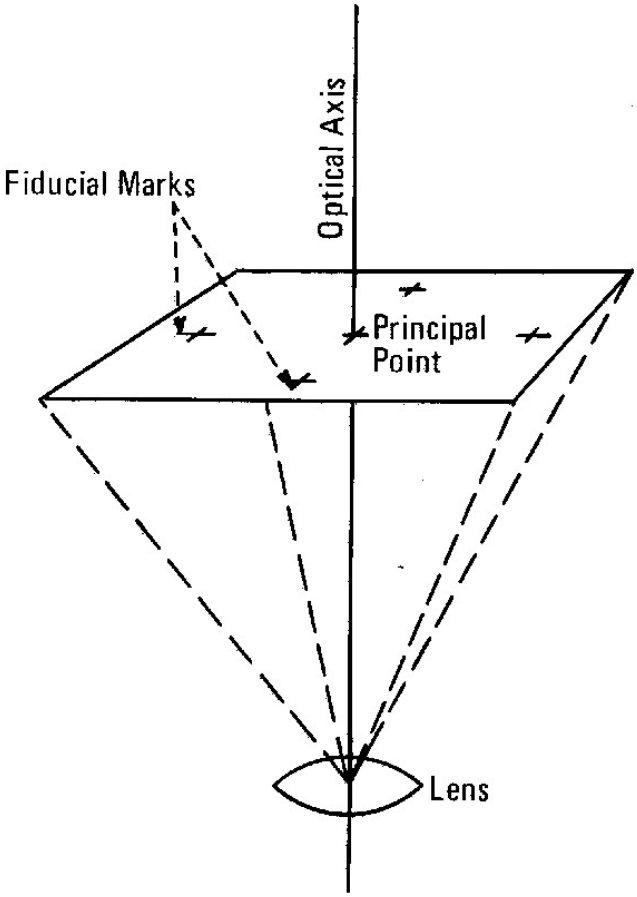

Figure 3.2: Principal Point,
http://www.fao.org/docrep/003/t0390e/T0390E48.gif

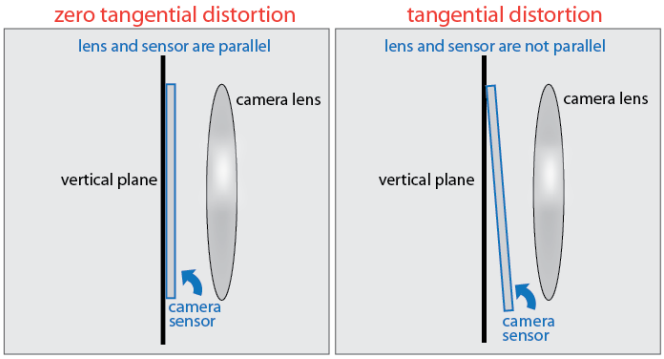

Figure 3.3: Tangential Distortion,
http://www.mathworks.com/help/vision/ref/cameracalibrator_tangentialdistortion.png

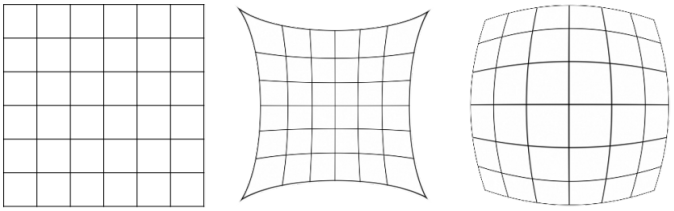

Figure 3.4: Radial Distortion,
http://www.intechopen.com/source/html/44946/media/image17.png

4 Possible Problems

One problem could be surface of the grid if it is not fixated on the plate properly. This could lead to unwanted bending of the grid. Another problem could occur if the grid is not being held still while taking the pictures. The images could become blurred and useless. If the checker board gets partly out of the image these images will become useless as well. The lighting conditions need to be good to ensure the distinction of the single checker cells.

5 Results

The parameters can be seen in 6. Figure 5.1 shows images of the extrinsic parameters and figure 5.2 the reprojection error.

(a) Camera Centered (b) World Centered

Figure 5.1: Extrinsic Camera Parameters

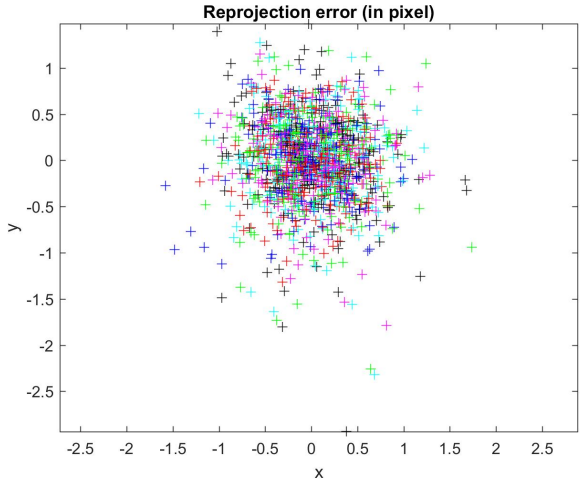

Figure 5.2: Reprojection Error

6 APPENDIX

```
% Intrinsic and Extrinsic Camera Parameters
%
% This script file can be directly executed under Matlab to recover the
% camera intrinsic and extrinsic parameters.
% IMPORTANT: This file contains neither the structure of the calibration
% objects nor the image coordinates of the calibration points.
%            All those complementary variables are saved in the complete
% matlab data file Calib_Results.mat.
% For more information regarding the calibration model visit
% http://www.vision.caltech.edu/bouguetj/calib_doc/


%-- Focal length:
fc = [ 1465.757474554883600 ; 1457.402140593278100 ];

%-- Principal point:
cc = [ 984.461621360877420 ; 552.451390384972800 ];

%-- Skew coefficient:
alpha_c = 0.000000000000000;

%-- Distortion coefficients:
kc = [ 0.014612236375303 ; 0.028401223072216 ; -0.003365882203774 ;...
    0.000782273655815 ; 0.000000000000000 ];

%-- Focal length uncertainty:
fc_error = [ 4.381633097548710 ; 4.325015986403185 ];

%-- Principal point uncertainty:
cc_error = [ 5.596179705904434 ; 4.372004465344061 ];

%-- Skew coefficient uncertainty:
alpha_c_error = 0.000000000000000;

%-- Distortion coefficients uncertainty:
kc_error = [ 0.011523877593091 ; 0.059663485150096 ; 0.001003656326247 ;...
    0.001399652634250 ; 0.000000000000000 ];

%-- Image size:
nx = 1920;
ny = 1080;


%-- Various other variables (may be ignored if you do not use the
% Matlab Calibration Toolbox):
%-- Those variables are used to control which intrinsic parameters
% should be optimized

n_ima = 27;  % Number of calibration images
est_fc = [ 1 ; 1 ]; % Estimation indicator of the two focal variables
est_aspect_ratio = 1; % Estimation indicator of the aspect ratio fc(2)/fc(1)
center_optim = 1; % Estimation indicator of the principal point
est_alpha = 0;  % Estimation indicator of the skew coefficient
% Estimation indicator of the distortion coefficients
est_dist = [ 1 ; 1 ; 1 ; 1 ; 0 ];


%-- Extrinsic parameters:
%-- The rotation (omc_kk) and the translation (Tc_kk)
```

```
% vectors for every calibration image and their uncertainties

%-- Image #1:
omc_1 = [ 2.217381e+00 ; 2.127725e+00 ; -3.546981e-01 ];
Tc_1  = [ -1.196360e+02 ; -8.122854e+01 ; 4.151356e+02 ];
omc_error_1 = [ 2.893951e-03 ; 3.415952e-03 ; 7.032084e-03 ];
Tc_error_1  = [ 1.592998e+00 ; 1.251145e+00 ; 1.397375e+00 ];

%-- Image #2:
omc_2 = [ 2.141047e+00 ; 2.127049e+00 ; -6.266029e-01 ];
Tc_2  = [ -5.027920e+01 ; -1.016662e+02 ; 5.035543e+02 ];
omc_error_2 = [ 2.980127e-03 ; 3.463614e-03 ; 7.169127e-03 ];
Tc_error_2  = [ 1.942652e+00 ; 1.502589e+00 ; 1.534351e+00 ];

%-- Image #3:
omc_3 = [ 2.128780e+00 ; 2.239639e+00 ; -2.950058e-01 ];
Tc_3  = [ -1.040858e+02 ; -1.260490e+02 ; 6.061448e+02 ];
omc_error_3 = [ 4.392796e-03 ; 5.264673e-03 ; 1.037824e-02 ];
Tc_error_3  = [ 2.336011e+00 ; 1.820693e+00 ; 2.016872e+00 ];

%-- Image #4:
omc_4 = [ 2.175922e+00 ; 2.183784e+00 ; -1.889158e-01 ];
Tc_4  = [ -1.217660e+02 ; -8.666442e+01 ; 3.400920e+02 ];
omc_error_4 = [ 2.608605e-03 ; 3.164193e-03 ; 6.330359e-03 ];
Tc_error_4  = [ 1.313197e+00 ; 1.031630e+00 ; 1.223513e+00 ];

%-- Image #5:
omc_5 = [ 1.606014e+00 ; 2.461937e+00 ; -7.863645e-01 ];
Tc_5  = [ -6.785092e+01 ; -1.275436e+02 ; 4.806674e+02 ];
omc_error_5 = [ 1.887824e-03 ; 3.845927e-03 ; 5.982527e-03 ];
Tc_error_5  = [ 1.855856e+00 ; 1.448520e+00 ; 1.451915e+00 ];

%-- Image #6:
omc_6 = [ -1.502451e+00 ; -2.599423e+00 ; 7.428499e-01 ];
Tc_6  = [ -2.335813e+01 ; -1.538727e+02 ; 6.088418e+02 ];
omc_error_6 = [ 3.725958e-03 ; 3.828480e-03 ; 6.790942e-03 ];
Tc_error_6  = [ 2.355812e+00 ; 1.832820e+00 ; 1.865070e+00 ];

%-- Image #7:
omc_7 = [ 2.240680e+00 ; 2.097087e+00 ; -2.639643e-01 ];
Tc_7  = [ -1.201841e+02 ; -7.873336e+01 ; 4.511668e+02 ];
omc_error_7 = [ 3.556346e-03 ; 3.842302e-03 ; 8.050391e-03 ];
Tc_error_7  = [ 1.731135e+00 ; 1.358984e+00 ; 1.530801e+00 ];

%-- Image #8:
omc_8 = [ -1.919356e+00 ; -2.188765e+00 ; 1.331598e-01 ];
Tc_8  = [ -5.151171e+01 ; -6.298458e+01 ; 5.434395e+02 ];
omc_error_8 = [ 4.166358e-03 ; 5.701500e-03 ; 9.718333e-03 ];
Tc_error_8  = [ 2.075409e+00 ; 1.631228e+00 ; 1.849512e+00 ];

%-- Image #9:
omc_9 = [ -1.939389e+00 ; -2.101871e+00 ; 6.917473e-02 ];
Tc_9  = [ -7.062690e+01 ; -9.579143e+01 ; 4.676949e+02 ];
omc_error_9 = [ 3.628769e-03 ; 4.393511e-03 ; 7.887063e-03 ];
Tc_error_9  = [ 1.797193e+00 ; 1.405496e+00 ; 1.587654e+00 ];

%-- Image #10:
omc_10 = [ 2.089082e+00 ; 2.184436e+00 ; -1.030913e-01 ];
Tc_10  = [ -7.040070e+01 ; -8.447812e+01 ; 3.851613e+02 ];
omc_error_10 = [ 3.194480e-03 ; 3.411773e-03 ; 7.049182e-03 ];
Tc_error_10  = [ 1.486036e+00 ; 1.153239e+00 ; 1.311667e+00 ];
```

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%-- Image #11:
omc_11 = [ -2.140962e+00 ; -2.139162e+00 ; 7.682513e-02 ];
Tc_11  = [ -6.025111e+01 ; -6.304408e+01 ; 4.274958e+02 ];
omc_error_11 = [ 3.761568e-03 ; 4.417491e-03 ; 8.612685e-03 ];
Tc_error_11  = [ 1.642342e+00 ; 1.287334e+00 ; 1.458320e+00 ];

%-- Image #12:
omc_12 = [ -1.836352e+00 ; -2.376002e+00 ; 3.768868e-01 ];
Tc_12  = [ -3.619338e+01 ; -1.187487e+02 ; 6.404012e+02 ];
omc_error_12 = [ 4.741391e-03 ; 5.930297e-03 ; 1.112378e-02 ];
Tc_error_12  = [ 2.461902e+00 ; 1.916697e+00 ; 2.058761e+00 ];

%-- Image #13:
omc_13 = [ 2.062866e+00 ; 2.341004e+00 ; -3.659577e-01 ];
Tc_13  = [ -8.629077e+01 ; -8.557770e+01 ; 6.230044e+02 ];
omc_error_13 = [ 5.034938e-03 ; 5.673743e-03 ; 1.138411e-02 ];
Tc_error_13  = [ 2.382998e+00 ; 1.869706e+00 ; 2.026898e+00 ];

%-- Image #14:
omc_14 = [ -2.106761e+00 ; -2.184729e+00 ; 3.404423e-01 ];
Tc_14  = [ -8.834061e+01 ; -8.779341e+01 ; 4.061891e+02 ];
omc_error_14 = [ 3.331390e-03 ; 3.128802e-03 ; 6.912831e-03 ];
Tc_error_14  = [ 1.558569e+00 ; 1.214777e+00 ; 1.334860e+00 ];

%-- Image #15:
omc_15 = [ 1.874027e+00 ; 2.207288e+00 ; -7.199680e-01 ];
Tc_15  = [ -1.068217e+02 ; -1.225279e+02 ; 4.603490e+02 ];
omc_error_15 = [ 2.002646e-03 ; 3.634021e-03 ; 5.999640e-03 ];
Tc_error_15  = [ 1.785147e+00 ; 1.394994e+00 ; 1.449171e+00 ];

%-- Image #16:
omc_16 = [ -1.957080e+00 ; -2.016839e+00 ; -6.863056e-02 ];
Tc_16  = [ -1.082697e+02 ; -8.458730e+01 ; 4.406259e+02 ];
omc_error_16 = [ 3.221934e-03 ; 3.744844e-03 ; 6.891196e-03 ];
Tc_error_16  = [ 1.693352e+00 ; 1.332652e+00 ; 1.541180e+00 ];

%-- Image #17:
omc_17 = [ -1.826815e+00 ; -2.300399e+00 ; 3.414917e-01 ];
Tc_17  = [ -7.339747e+01 ; -1.111823e+02 ; 4.379035e+02 ];
omc_error_17 = [ 3.184175e-03 ; 3.654842e-03 ; 6.769655e-03 ];
Tc_error_17  = [ 1.683827e+00 ; 1.311704e+00 ; 1.427741e+00 ];

%-- Image #18:
omc_18 = [ 2.165837e+00 ; 2.208638e+00 ; -8.557430e-02 ];
Tc_18  = [ -1.105036e+02 ; -8.487271e+01 ; 3.326578e+02 ];
omc_error_18 = [ 2.778283e-03 ; 3.137409e-03 ; 6.400241e-03 ];
Tc_error_18  = [ 1.289053e+00 ; 1.010617e+00 ; 1.185165e+00 ];

%-- Image #19:
omc_19 = [ -2.165090e+00 ; -2.225277e+00 ; 1.583389e-01 ];
Tc_19  = [ -8.144123e+01 ; -1.140361e+02 ; 6.098672e+02 ];
omc_error_19 = [ 6.498244e-03 ; 6.412186e-03 ; 1.419403e-02 ];
Tc_error_19  = [ 2.346139e+00 ; 1.827846e+00 ; 2.129333e+00 ];

%-- Image #20:
omc_20 = [ -2.201811e+00 ; -2.209893e+00 ; -1.249030e-01 ];
Tc_20  = [ -1.308987e+02 ; -5.648756e+01 ; 5.258946e+02 ];
omc_error_20 = [ 5.809376e-03 ; 5.838699e-03 ; 1.261572e-02 ];
Tc_error_20  = [ 2.024147e+00 ; 1.604874e+00 ; 2.001575e+00 ];
```

```
%-- Image #21:
omc_21 = [ 1.670704e+00 ; 1.774852e+00 ; -6.131726e-01 ];
Tc_21  = [ -1.062747e+02 ; -8.679470e+01 ; 4.177791e+02 ];
omc_error_21 = [ 2.253578e-03 ; 3.383864e-03 ; 4.711023e-03 ];
Tc_error_21  = [ 1.604375e+00 ; 1.262643e+00 ; 1.309090e+00 ];

%-- Image #22:
omc_22 = [ 1.571481e+00 ; 1.621853e+00 ; -8.639186e-01 ];
Tc_22  = [ -1.043808e+02 ; -4.834455e+01 ; 3.997797e+02 ];
omc_error_22 = [ 2.361868e-03 ; 3.349770e-03 ; 4.317338e-03 ];
Tc_error_22  = [ 1.526646e+00 ; 1.211137e+00 ; 1.143479e+00 ];

%-- Image #23:
omc_23 = [ 1.644251e+00 ; 1.661079e+00 ; -6.108240e-01 ];
Tc_23  = [ -7.352835e+01 ; -8.091121e+01 ; 4.019785e+02 ];
omc_error_23 = [ 2.467379e-03 ; 3.289905e-03 ; 4.415655e-03 ];
Tc_error_23  = [ 1.542390e+00 ; 1.202506e+00 ; 1.226964e+00 ];

%-- Image #24:
omc_24 = [ 1.790685e+00 ; 1.773067e+00 ; -3.588352e-01 ];
Tc_24  = [ -9.602637e+01 ; -9.192933e+01 ; 3.875324e+02 ];
omc_error_24 = [ 2.377675e-03 ; 3.224774e-03 ; 4.831647e-03 ];
Tc_error_24  = [ 1.490910e+00 ; 1.163177e+00 ; 1.288516e+00 ];

%-- Image #25:
omc_25 = [ -2.079182e+00 ; -1.908843e+00 ; 7.872285e-01 ];
Tc_25  = [ -8.797202e+01 ; -5.341411e+01 ; 4.353577e+02 ];
omc_error_25 = [ 3.424505e-03 ; 2.419583e-03 ; 5.526537e-03 ];
Tc_error_25  = [ 1.661250e+00 ; 1.303104e+00 ; 1.222265e+00 ];

%-- Image #26:
omc_26 = [ -2.004838e+00 ; -1.778521e+00 ; 6.744807e-01 ];
Tc_26  = [ -5.167457e+01 ; -6.186029e+01 ; 4.846911e+02 ];
omc_error_26 = [ 3.297582e-03 ; 2.698299e-03 ; 5.657830e-03 ];
Tc_error_26  = [ 1.850472e+00 ; 1.441739e+00 ; 1.332774e+00 ];

%-- Image #27:
omc_27 = [ -1.834439e+00 ; -2.024098e+00 ; 3.835311e-01 ];
Tc_27  = [ -1.857379e+01 ; -8.645682e+01 ; 4.880777e+02 ];
omc_error_27 = [ 3.166774e-03 ; 3.908599e-03 ; 6.634576e-03 ];
Tc_error_27  = [ 1.868073e+00 ; 1.452712e+00 ; 1.502941e+00 ];
```

REFERENCES

[1] Description of the calibration parameters. http://www.vision.caltech.edu/bouguetj/calib_doc/htmls/parameters.html. Accessed: 2016-05-01.

[2] First calibration example - corner extraction, calibration, additional tools. http://www.vision.caltech.edu/bouguetj/calib_doc/htmls/example.html. Accessed: 2016-05-01.

[3] Wikipedia. https://en.wikipedia.org. Accessed: 2016-05-01.