Computer Vision Assignment Report

Assignment 1 (Camera Calibration)

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1 Introduction

The purpose of this assignment is to be familiar with camera calibration. The algortithms used for this purpose are DLT, RANSAC, and Zhang's method.

2 DLT

DLT uses at least 6 image points to estimate the camera parameters. The points should not lie on a plane, else DLT will produce degenerate results.

2.1 Code

```
imagePoints = [ 488, 140, 1;
    404, 134, 1;
    388, 238, 1;
    493, 57, 1;
    407, 51, 1;
    474, 246, 1];

worldPoints = [0, 36, 0, 1;
    36, 36, 0, 1;
```

```
    36, 0, 36, 1;
    0, 72, 0, 1;
    36, 72, 0, 1;
    0, 0, 36, 1];


A = zeros(12, 12);
k = 1;
for i = 1:6
    imgPt = imagePoints(i, 1);
    A(k, 1:4) = -worldPoints(i,:);
    A(k,5:8) = zeros(1,4);
    A(k,9:12) = [imgPt*worldPoints(i,1),
                 imgPt*worldPoints(i,2),
                 imgPt*worldPoints(i,3),
                 imgPt];
    k = k + 1;

    imgPt = imagePoints(i, 2);
    A(k,1:4) = zeros(1,4);
    A(k, 5:8) = -worldPoints(i,:);
    A(k,9:12) = [imgPt*worldPoints(i,1),
                 imgPt*worldPoints(i,2),
                 imgPt*worldPoints(i,3),
                 imgPt];
    k = k + 1;
end

[U, S, V] = svd(A);
singV = diag(S);
[~, indx] = sort(singV);
p = V(:, indx(1));
p = reshape(p, [4,3])';
estimatedImg = p*worldPoints';
imgEst = round(estimatedImg ./ repmat(estimatedImg(3,:),3,1))';
imagePoints
H = p(:,1:3);
invH = inv(H);
```

```
[invR, invK] = qr(invH);
R = invR';
K = inv(invK);
```

2.2 Input

The input to DLT are image points and their correspondinf world coordinates. For this experiment, 6 image points have been chosen.

2.3 Output

There were no re-projection error for the chosen image coordinates. It has been observed that DLT gives very high accuracy in estimating the camera parameters and thus very low re-projection error.
The image coordinates of the corner points were as follows:

```
imagePoints = [ 488, 140, 1;
    404, 134, 1;
    388, 238, 1;
    493, 57, 1;
    407, 51, 1;
    474, 246, 1];
```

The projected image coordinates estimated from the camera matrix are as follows:

```
  487.9798   140.2380     1.0000
  404.0205   133.7647     1.0000
  387.9901   238.1065     1.0000
  493.0110    56.8638     1.0000
  406.9888    51.1346     1.0000
  474.0100   245.8923     1.0000
```

The parameters of the camera matrix are as follows:

2.4 Camera Projection Matrix

```
P = [-0.0041   -0.0003   -0.0017    0.9102
     -0.0003   -0.0043    0.0007    0.4140
      0.0000   -0.0000   -0.0000    0.0019]
```

2.5 Intrinsic Parameters

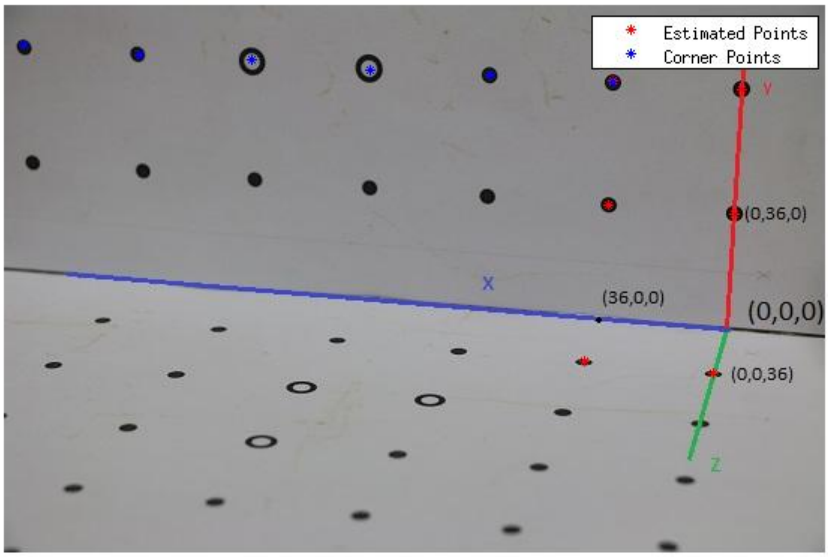
$$K = \begin{bmatrix} 0.0007 & 0.0043 & -0.0365 \\ 0 & 0.0002 & -0.0080 \\ 0 & 0 & -0.0002 \end{bmatrix}$$

2.6 Extrinsic Parameters

$$R = \begin{bmatrix} -0.9070 & 0.1404 & -0.3970 \\ -0.3594 & -0.7495 & 0.5559 \\ -0.2195 & 0.6469 & 0.7303 \end{bmatrix}$$

$$C = \begin{bmatrix} 54.9197 \\ -207.6365 \\ -632.9154 \end{bmatrix}$$

2.7 WireFrame of Estimated Points



3 RANSAC

Random sample consensus (RANSAC) is an iterative method to estimate parameters of a mathematical model from a set of observed data which contains outliers. RANSAC is used for camera calibration to estimate the camera matrix with the least re-projection error. The best estimation of the camera matrix is chosen to be the one with minimum number of outliers.
The average reprojection error of the experiment by RANSAC is 11.7119.

3.1 Code

```
imgPts = [14, 27, 1;
91, 34, 1;
166, 37, 1;
245, 44, 1;
325, 47, 1;
407, 52, 1;
493, 57, 1;
20, 104, 1;
94, 110, 1;
168, 117, 1;
245, 122, 1;
323, 128, 1;
404, 134, 1;
488, 140, 1;
398, 209, 1;
474, 246, 1;
465, 279, 1;
455, 316, 1;
444, 360, 1;
387, 236, 1;
304, 231, 1;
224, 223, 1;
114, 216, 1;
66, 210, 1;
34, 240, 1;
117, 246, 1;
```

```
200, 254, 1];

worldPts = [216, 72, 0, 1;
180, 72, 0, 1;
144, 72, 0, 1;
108, 72, 0, 1;
72, 72, 0, 1;
36, 72, 0, 1;
0, 72, 0, 1;
216, 36, 0, 1;
180, 36, 0, 1;
144, 36, 0, 1;
108, 36, 0, 1;
72, 36, 0, 1;
36, 36, 0, 1;
0, 36, 0, 1;
36, 0, 0, 1
0, 0, 36, 1;
0, 0, 72, 1;
0, 0, 108, 1;
0, 0, 144, 1;
36, 0, 36, 1;
72, 0, 36, 1;
108, 0, 36, 1;
144, 0, 36, 1;
216, 0, 36, 1;
216, 0, 72, 1;
144, 0, 72, 1;
108, 0, 72, 1];

err = 0;
mnErr = 5000000;
p = zeros(3,4);
est = zeros(size(imgPts));

for iter = 1:1000
    indices = randperm(size(worldPts, 1), 6)
    P = DLT(imgPts(indices,:), worldPts(indices, :));
```

```
    estimatedImg = P*worldPts';
    imgEstimated = round(estimatedImg ./ repmat(estimatedImg(3,:),3,1));
    imgEstimated = imgEstimated';
    err = sum(sqrt(sum((imgPts - imgEstimated).^2,2)))/size(imgPts,1);
    if mnErr >= err
        p = P;
        mnErr = err;
    end
end

estimatedImg = p*worldPts';
imgEstimated = round(estimatedImg ./ repmat(estimatedImg(3,:),3,1));
imgEstimated = imgEstimated';
```

3.2 Input

The input to RANSAC are a set of 27 image and their correspoding world points. The actual image points are as follows:

```
 14    27    1
 91    34    1
166    37    1
245    44    1
325    47    1
407    52    1
493    57    1
 20   104    1
 94   110    1
168   117    1
245   122    1
323   128    1
404   134    1
488   140    1
398   209    1
474   246    1
465   279    1
455   316    1
444   360    1
387   236    1
```

304	231	1
224	223	1
114	216	1
66	210	1
34	240	1
117	246	1
200	254	1

3.3 Output

There are few errors in the estimation of image points from the camera matrix. This is due to radial distortion.
The estimated image points are as follows

3	24	1
81	29	1
160	35	1
240	40	1
323	46	1
407	51	1
493	57	1
9	103	1
85	109	1
162	115	1
241	121	1
322	127	1
404	134	1
488	140	1
401	213	1
474	246	1
464	275	1
453	307	1
440	343	1
388	238	1
304	230	1
221	223	1
141	216	1
−16	202	1

−50	226	1
114	242	1
199	250	1

The parameters of the camera matrix are as follows:

3.3.1 Camera Projection Matrix

$$P = \begin{bmatrix} -0.0041 & -0.0003 & -0.0017 & 0.9102 \\ -0.0003 & -0.0043 & 0.0007 & 0.4140 \\ 0.0000 & -0.0000 & -0.0000 & 0.0019 \end{bmatrix}$$

3.3.2 Intrinsic Parameters

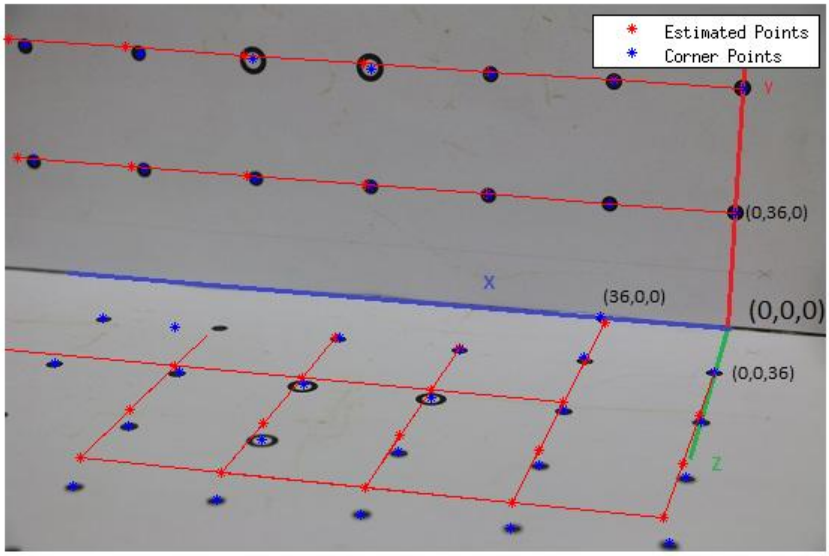
$$K = \begin{bmatrix} 0.0043 & 0.0001 & -0.0009 \\ 0 & 0.0043 & -0.0011 \\ 0 & 0 & -0.0000 \end{bmatrix}$$

3.3.3 Extrinsic Parameters

$$R = \begin{bmatrix} -0.9754 & 0.0205 & -0.2193 \\ -0.1107 & -0.9062 & 0.4081 \\ -0.1904 & 0.4223 & 0.8862 \end{bmatrix}$$

$$C = \begin{bmatrix} 54.9197 \\ -207.6365 \\ -632.9154 \end{bmatrix}$$

3.4 Output Image


Estimated Points
Corner Points
Y
(0,36,0)
X
(36,0,0)
(0,0,0)
(0,0,36)
Z

4 Radial Distortion

4.1 Code for Distortion Parameter Estimation

```
imgPts = [14, 27, 1;
91, 34, 1;
166, 37, 1;
245, 44, 1;
325, 47, 1;
407, 52, 1;
493, 57, 1;
20, 104, 1;
94, 110, 1;
168, 117, 1;
245, 122, 1;
323, 128, 1;
404, 134, 1;
488, 140, 1;
398, 209, 1;
474, 246, 1;
465, 279, 1;
455, 316, 1;
444, 360, 1;
387, 236, 1;
304, 231, 1;
224, 223, 1;
114, 216, 1;
66, 210, 1;
34, 240, 1;
117, 246, 1;
200, 254, 1];

I = imread('IMG_5464.JPG');
gray = rgb2gray(I);
rows = size(I,1);
cols = size(I,2);
d = min(rows, cols) / 2;
centerX = cols/2;
```

```
centerY = rows/2;
;

mnErr = 5000000;
estK1 = 0;
estK2 = 0;
estPts = [];
for k1 = -0.15:0.0001:0.1
    for k2 = -0.15:0.0001:0.1
        UnXList = [];
        UnYList = [];
        for i = 1:size(imgPts,1)
            xd = imgPts(i,1);
            yd = imgPts(i,2);
            %xd = (x - centerX);
            %yd = (y - centerY);
            r = sqrt((xd-centerX)^2 + (yd-centerY)^2);
            Lr = 1 + k1*r^1 + k2*r^2;
            xUn = xd/Lr;
            yUn = yd/Lr;
            UnXList = [UnXList;xUn];
            UnYList = [UnYList;yUn];
        end
        err = 0;
        for p = 1:size(UnXList,1)
            for q = p+1:size(UnXList,1)
                err = err + sqrt((UnXList(p) -
                 UnXList(q))^2 + (UnYList(p) -
                 UnYList(q))^2);
            end
        end
        if err < mnErr
            mnErr = err;
            estK1 = k1;
            estK2 = k2;
            estX = UnXList;
            estY = UnYList;
        end
```

```
    end
end
estK1
estK2
newPts = [estX, estY];
```

4.2 Output

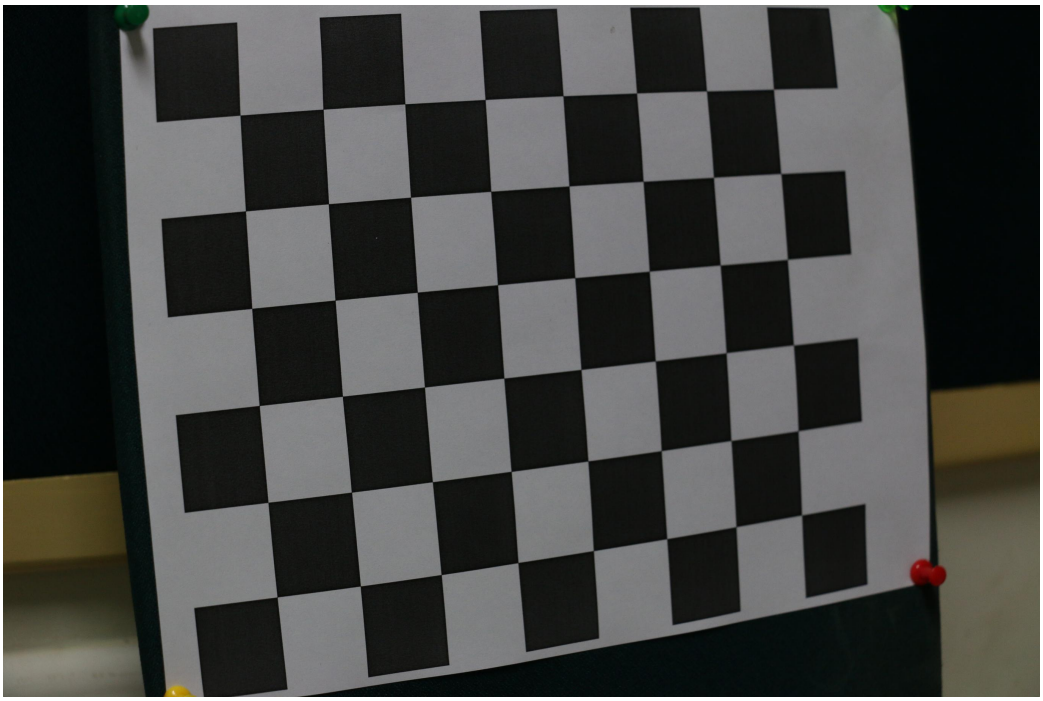
The radial distortion parameter K1 and K2 are 0.1 and 0.1.

4.3 Code for Radial Distortion Correction

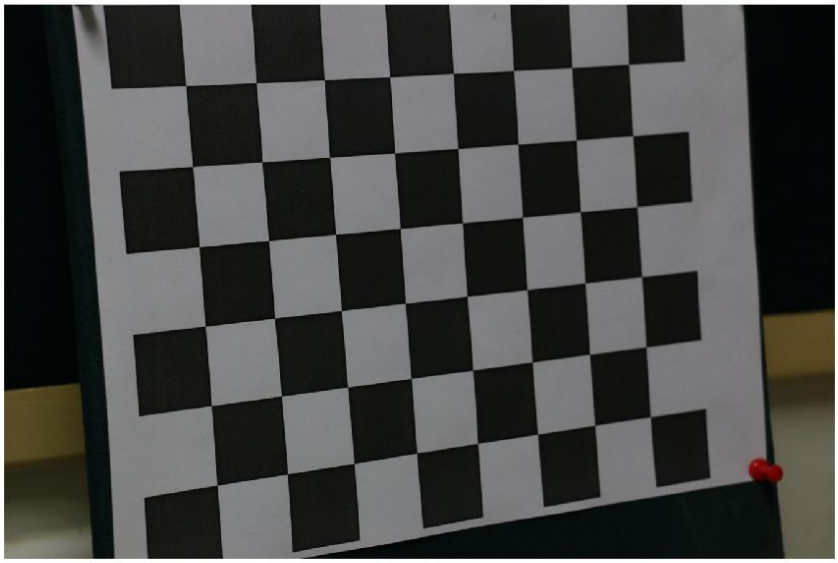
```
function correctRadial2()%I, k, varargin)
I = imread('distort.jpg');
k = 0.1;


     for i=1:3
       I2(:,:,i) = imdistcorrect(I(:,:,i),k, [0,0]);
     end
end

    function I3 = imdistcorrect(I,k, center)
    % Determine the size of the image to be distorted
    [M N]=size(I);
    %If Center is (0,0) then we use the center of the image, otherwise
    %should will be the coordintes of the image center
    center = [round(N/2) round(M/2)];

    %center = [1592,656];
    % Creates N x M (#pixels) x-y points
    [xi,yi] = meshgrid(1:N,1:M);
    % Creates converst the mesh into a colum vector of coordiantes relat
    % the center
    xt = xi(:) - center(1);
    yt = yi(:) - center(2);
    % Converts the x-y coordinates to polar coordinates
    [theta,r] = cart2pol(xt,yt);
```

```
% Calculate the maximum vector (image center to image corner) to be
% for normalization
R = sqrt(center(1)^2 + center(2)^2);
% Normalize the polar coordinate r to range between 0 and 1
r = r/R;
% Aply the r-based transformation

s = r.*(1./(1+k.*(r.^2)));
% un-normalize s
s2 = s * R;

% Convert back to cartesian coordinates
[ut,vt] = pol2cart(theta,s2);

u = reshape(ut,[M N]) + center(1);
v = reshape(vt,[M N]) + center(2);
tmap_B = cat(3,u,v);
resamp = makeresampler('cubic', 'fill');
I3 = tformarray(I,[],resamp,[2 1],[1 2],[],tmap_B,255);
end
```

4.4 Input Image



4.5 Output Image



4.6 DLT after radial Distortion

4.6.1 Camera Projection Matrix

p =

−0.0036	−0.0001	−0.0016	0.9110
0.0001	−0.0046	0.0009	0.4123
0.0000	−0.0000	−0.0000	0.0019

4.7 Intrinsic Parameter

K =

0.0036	0.0000	0.0014
0	0.0046	−0.0009
0	0	−0.0000

4.8 Extrinsic Parameter

R =

−0.7061	−0.1452	−0.6930
−0.1138	−0.9428	0.3135
−0.6989	0.3002	0.6492

C =

32.4343
−208.8298
−637.8236

4.9 Radial Corrected Input Points

```
imagePoints = [ 499, 134, 1;
    407, 132, 1;
    389, 239, 1;
    508, 46, 1;
```

```
414, 44, 1;
482, 251, 1];
```

4.10 Estimated Points

imgEst =

498.8616	135.4504	1.0000
407.1516	130.6297	1.0000
388.9188	239.6291	1.0000
508.0671	45.1816	1.0000
413.9260	44.7729	1.0000
482.0855	250.3377	1.0000

The reprojection error is about 6.1488.

4.11 Ransac after radial Distortion

4.11.1 Camera Projection Matrix

p =

−0.0036	−0.0001	−0.0016	0.8110
0.0001	−0.0046	0.0009	0.5723
0.0000	−0.0000	−0.0000	0.0119

4.12 Intrinsic Parameter

K =

0.0036	0.0000	0.0014
0	0.0046	−0.0009
0	0	−0.0000

4.13 Extrinsic Parameter

R =

−0.8161	−0.1452	−0.6890
−0.2038	−0.9428	0.6735
−0.5900	0.5002	0.6492

C =

$$\begin{matrix} 30.8653 \\ -100.8298 \\ -700.8236 \end{matrix}$$

5 Camera Calibration using Zhang's Method

Zhang's method finds the camera calibration from a number of images(at least 6) instead of a single image. For the experiment, 15 images were provided of which 8 were used by the algorithm. OpenCv has been used to estimate the camera matrix.

5.1 Input

The input to Zhang's method is a list of 15 checkerboard images at various distances and angles to the camera.

5.2 Output

The average re-projection error is 0.4764.

5.3 Per View Re-projection Errors

Views	1	2	3	4
Error	4.45612878e-01	4.16758776e-01	5.33244491e-01	5.22755444e-01
Views	5	6	7	8
Error	4.24562335e-01	3.42109889e-01	6.22883558e-01	4.48383838e-01

5.3.1 Distortion Coefficients

3.5641444594248478e-01	-7.6895267684771689e+00	0.	0.	1.6732388239861839e+02

5.3.2 Intrinsic Parameters

K = [2446.5393184376 0 499.5
0 2446.539318437 332.5
0 0 1]

5.4 Extrinsic Parameters

The rotation Matrix for the 15 views are as follows:

R1	0.00328069473509518	0.998912619274484	0.0465060866580260
	0.999946317117785	-0.00281989551069484	-0.00997051011166577
	-0.00982852606615983	0.0465363002772832	-0.998868245982357
R2	-0.0356069985049111	0.973419778601566	-0.226243400533034
	0.999364049672338	0.0342504197102492	-0.00991992803279924
	-0.00190732272450052	-0.226452739830966	-0.974020286617827
R3	0.0365368307623132	0.915017641760799	0.401755865251961
	0.999331230505276	-0.0328640307010605	-0.0160326923157348
	-0.00146687922384853	0.402072966950758	-0.915606453402747
R4	0.0679651778772694	0.813136553118128	0.578091411957730
	0.996931132559000	-0.0779121015186385	-0.00761717608949197
	0.0388465124656002	0.576835028773496	-0.815936454663683
R5	-0.0635202298042231	0.950205224343886	-0.305082303707057
	0.997860910669137	0.0652055572269334	-0.00467314297730612
	0.0154526167421529	-0.304726544521989	-0.952314522465928
R6	0.0518669790804445	0.975973546685526	0.211625737213468
	0.947606152533138	0.0187868466181493	-0.318888121565368
	-0.315202151265520	0.217077614148076	-0.923864120568262
R7	0.0401908020897435	0.927820004757500	0.370856762374877
	0.981616004448491	0.0326454995041404	-0.188053958141553
	-0.186587028589778	0.371596972718990	-0.909450917107746
R8	-0.0623138318300953	0.949210800564852	0.308408564170458
	0.970019193571399	-0.0151294334591594	0.242556930113938
	0.234903704665855	0.314276878459485	-0.919809922320921
R9	-0.0581970012124798	0.995199173414642	-0.0786874468049923
	0.949501926040635	0.0795228708827704	0.303516400630487
	0.308316722697616	-0.0570501379610603	-0.949571524564435
R10	-0.0381270991079316	0.846413218016220	0.531160040553730
	0.939201173670841	-0.151165707588780	0.308301936783565
	0.341244017806800	0.510620791994029	-0.789188777856390

R11	0.0107466817345443	0.918473568369743	0.395336329013470
	0.973493614925899	-0.0999396126037029	0.205723735944899
	0.228461573421442	0.382646544527417	-0.895202173495478

R12	0.0119983079303003	0.956752028421313	0.290657180744796
	0.993540108380768	0.0213971684467383	-0.111446014828677
	-0.112845441403459	0.290116730462353	-0.950314784195370

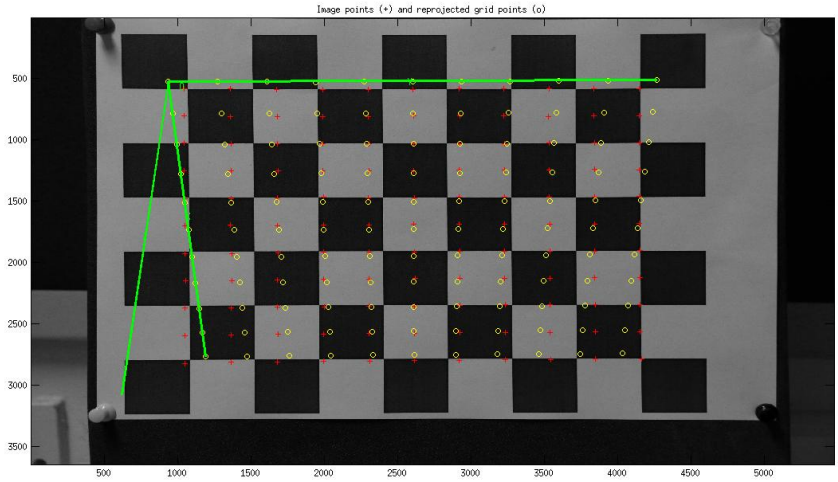
R13	-0.0696271289039611	0.997567173639519	0.00343467574194761
	0.926144930248936	0.0659206954650919	-0.371362397239666
	-0.370685353223976	-0.0226758899772364	-0.928481649209588

R14	0.0611553569612693	0.885656893724661	0.460295436554529
	0.931613635038752	0.114880161528756	-0.344816739003502
	-0.358268136072443	0.449904895600295	-0.818064500873902

R15	0.0411791011910335	0.911750587222643	0.408674868721168
	0.904242559502035	0.139986209766458	-0.403421931308190
	-0.425029028667816	0.386153761828609	-0.818679178320364

5.5 WireFrame Depiction on Estimated Image Points

Out of 15 images, some of the images with the estimated corners are as follows



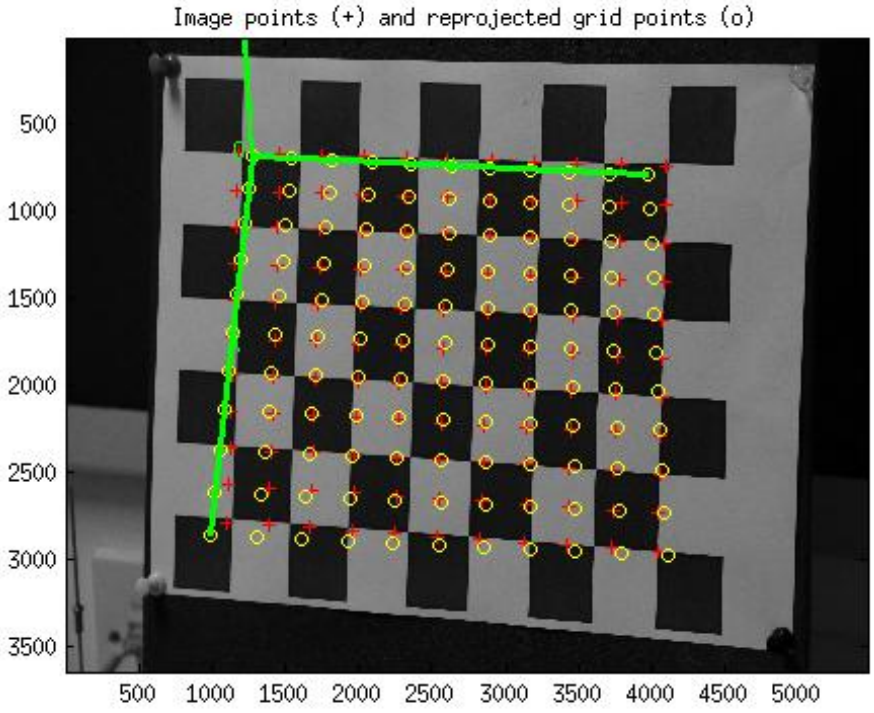


Image points (+) and reprojected grid points (o)
500
1000
1500
2000
2500
3000
3500
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

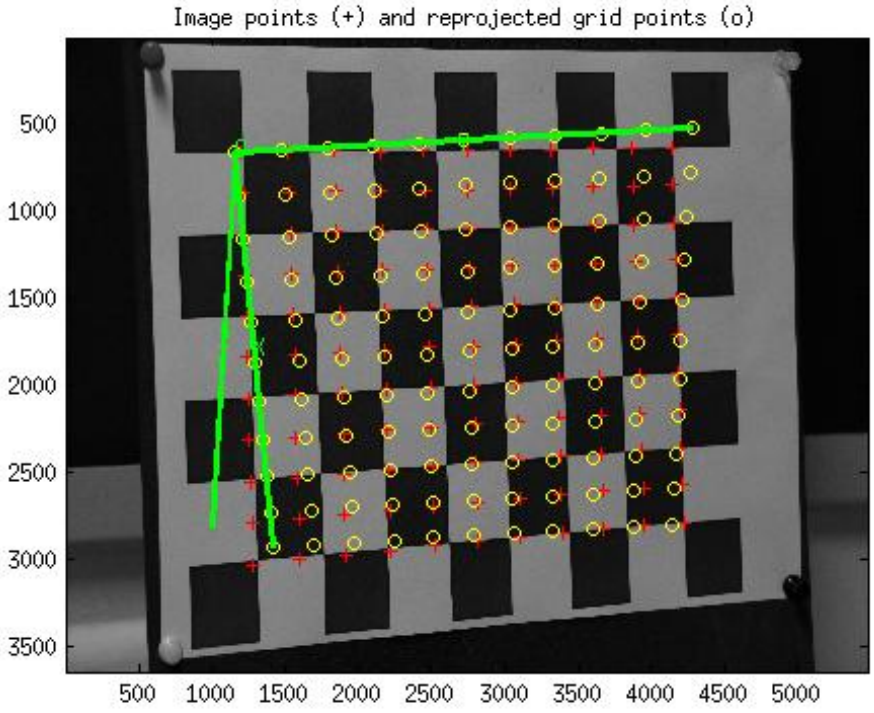


Image points (+) and reprojected grid points (o)
500
1000
1500
2000
2500
3000
3500
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

6 Personal Camera Calibration

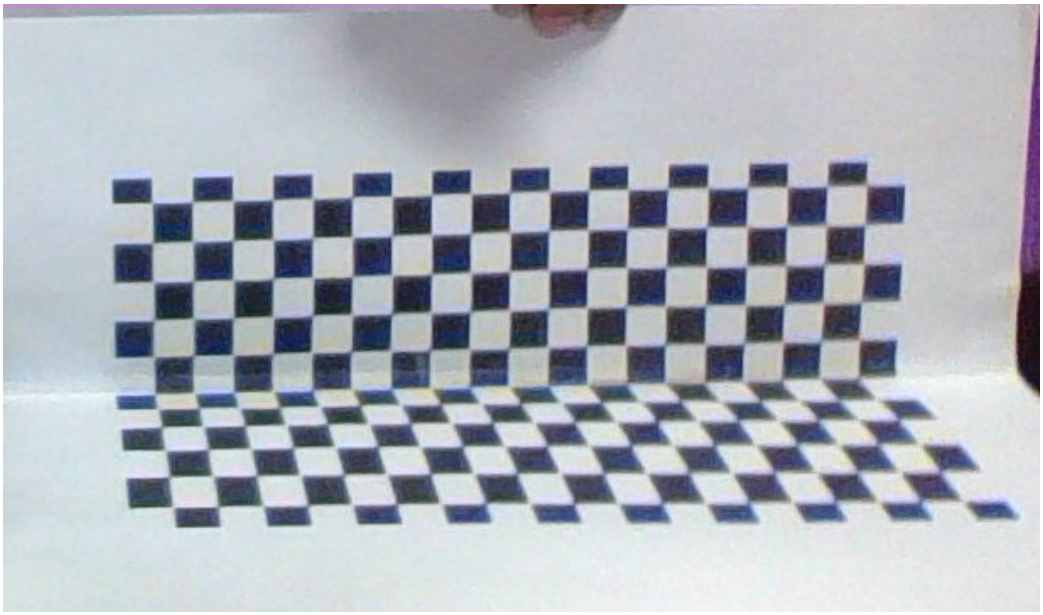
6.1 DLT

6.2 Code

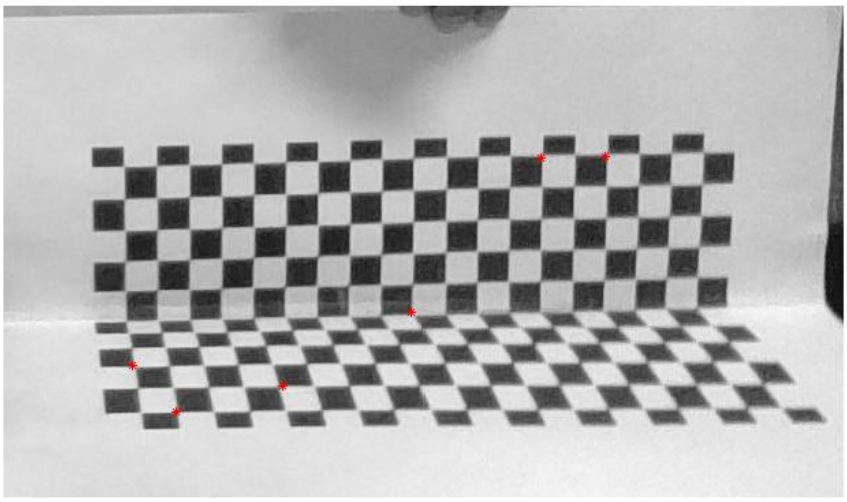
```
close all;
I = imread('Checkerboard4.jpg');
figure;
imshow(I);
I = rgb2gray(I);
C = corner(I, 'harris');
figure;
imshow(I);
hold on;
plot(C(100:104,1),C(100:104,2),'r*');
plot(C(105,1), C(105,2), 'r*');

imgCoord = [C(100:104,:), ; C(106,:)];
imgCoord = [imgCoord, repmat(1,6,1)]
worldCoord = [15.7, 0.7,0,1;
              11.2, 6.3, 0,1;
              1.0, 6.3, 3.4, 1;
              2.1, 6.3, 5.6, 1;
              18, 0.7, 0, 1;
              5.7, 6.3, 4.6,1];

          DLT(imgCoord, worldCoord)
```

6.3 Input

To estimate the camera parameters, the following image of a checkerboard is used



After corner points are detected by Harris corner detector, the camera parameters are estimated.



The world coordinates are as follows:

```
15.7, 0.7,0,1;
11.2, 6.3, 0,1;
1.0, 6.3, 3.4,1;
2.1, 6.3, 5.6, 1;
18, 0.7, 0, 1;
5.7, 6.3, 4.6,1
```

6.4 Output

The actual image coordinates as calculated by Harris Corner Detector is

```
393   112     1
298   225     1
 95   264     1
127   298     1
440   111     1
204   279     1
```

The estimated image coordinates of after projection is

```
393.9466   114.3111    1.0000
297.6838   224.1224    1.0000
 95.2003   264.3033    1.0000
125.8565   294.3272    1.0000
439.0968   108.6573    1.0000
205.2880   283.4391    1.0000
```

6.5 Projection Matrix P

-0.0410	0.0902	0.0032	-0.7749
0.0150	-0.0072	-0.0007	-0.6240
0.0001	0.0003	0.0001	-0.0046

6.5.1 Intrinsic Parameter K

-0.0237	-0.0611	0.0743
0	0.0163	-0.0037
0	0	0.0003

6.5.2 Extrinsic Parameter R

-0.1225	-0.3521	0.9279
0.9705	-0.2381	0.0377
0.2077	0.9052	0.3709

6.5.3 Extrinsic Parameter C

-55.1245	-36.4208	77.3984

6.6 RANSAC

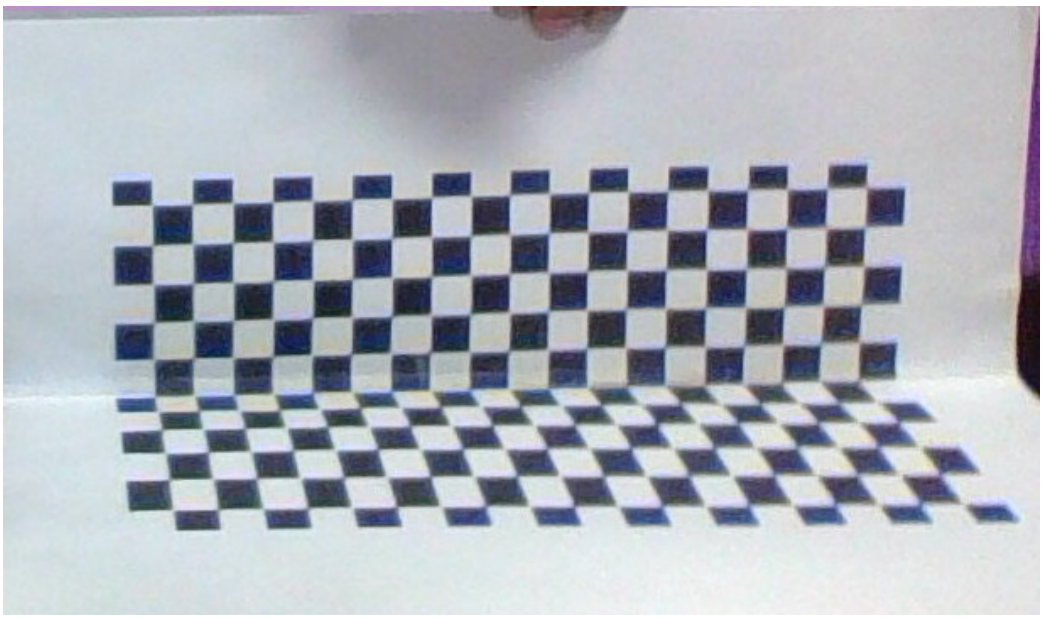
6.7 Code

```
 close all;
I = imread('Checkerboard4.jpg');
figure;
imshow(I);
I = rgb2gray(I);
C = corner(I, 'harris');
figure;
imshow(I);
hold on;
plot(C(100:104,1),C(100:104,2),'r*');
plot(C(106:114,1), C(106:114,2),'r*');

imgCoord = [C(100:104,:), ; C(106:114,:)];
imgCoord = [imgCoord, repmat(1,size(imgCoord,1),1)]
worldCoord = [15.7, 0.7,0,1;
              11.2, 6.3, 0,1;
              1.0, 6.3, 3.4, 1;
              2.1, 6.3, 5.6, 1;
              18, 0.7, 0, 1;
              5.7, 6.3, 4.6,1;
              13.6, 4.1, 1,1;
              3.4,5.2,0,1;
              7.8, 6.3, 1,1;
              12.4,1.7,0,1;
              3.4, 2.9,0,1;
```

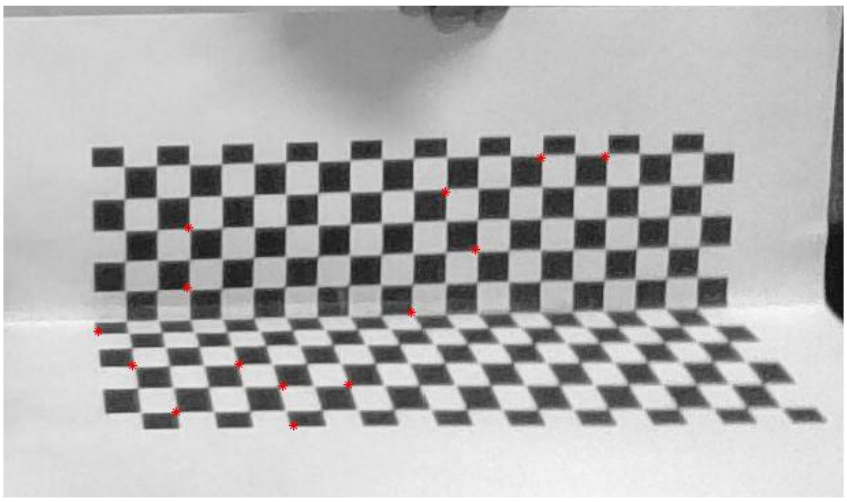
```
    5.7,  6.3,  6.4,1;
    0,6.3,1.1,1;
    4.5,  6.3,3.4,1];
[p, K, R, c, imgEstimated] = RANSAC(imgCoord, worldCoord);
```

6.8 Input

To estimate the camera parameters, the following image of a checkerboard is used



After corner points are detected by Harris corner detector, the camera parameters are estimated.



The world coordinates are as follows:

```
                15.7,  0.7,0,1;
11.2,  6.3,  0,1;
1.0,  6.3,  3.4,  1;
2.1,  6.3,  5.6,  1;
18,  0.7,  0,  1;
5.7,  6.3,  4.6,1;
13.6,  4.1,  1,1;
3.4,5.2,0,1;
7.8,  6.3,  1,1;
12.4,1.7,0,1;
3.4,  2.9,0,1;
5.7,  6.3,  6.4,1;
0,6.3,1.1,1;
4.5,  6.3,3.4,1
```

6.9 Output

The RMS error of the estimated and actual image coordiantes, is 6.2812. The actual image coordinates as calculated by Harris Corner Detector is

```
393    112      1
298    225      1
 95    264      1
127    298      1
440    111      1
204    279      1
345    179      1
135    207      1
252    278      1
323    137      1
136    163      1
212    308      1
 70    239      1
173    263      1
```

The estimated image coordinates of after projection is

```
389    113      1
```

298	225	1
95	264	1
126	292	1
440	111	1
204	279	1
357	190	1
135	206	1
231	237	1
319	135	1
136	163	1
214	303	1
70	239	1
171	264	1

6.10 Projection Matrix P

0.1305	-0.0095	0.0002	0.5308
-0.0104	0.1189	0.0313	0.8281
-0.0000	-0.0001	-0.0002	0.0073

6.10.1 Intrinsic Parameter K

-0.1222	0.0391	0.0258
0	-0.1057	0.0637
0	0	-0.0002

6.10.2 Extrinsic Parameter R

-0.9482	-0.1556	0.2771
0.2302	-0.9373	0.2615
0.2190	0.3118	0.9246

6.10.3 Extrinsic Parameter C

5.7456	21.6508	-53.9559

6.11 Zhang Method

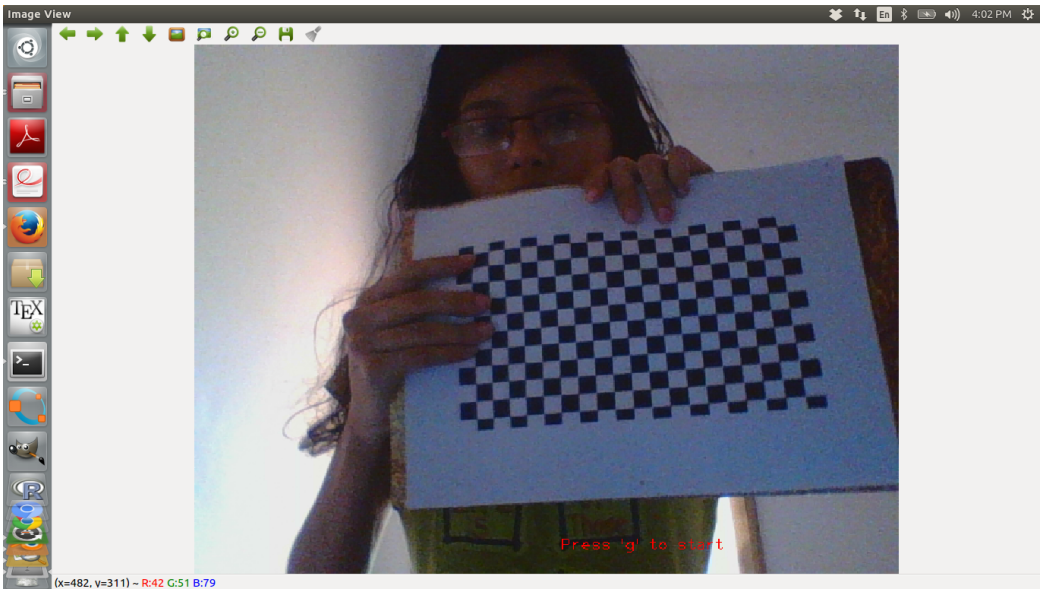
OpenCv's implementation of Zhang's method is used for this experiment. A video of checkerboard print out is the input to the program. The results produce the laptop camera parameters.

6.12 Input

The input to opencv's Zhang method was a video captured by my laptop camera. The configuration file was modified with the following parameters:

```
<BoardSize_Width> 19</BoardSize_Width>
  <BoardSize_Height>11</BoardSize_Height>

  <!-- The size of a square in some user defined metric system (pixel,
  <Square_Size>29</Square_Size>
```

A screenshot for the input video is as follows:



6.13 Output

The output was produced in an xml file.

6.14 Average Re-Projection Error

The average re-projection error is 1.8200765999238961.

6.15 Per view Re-projection Error

view	1	2	3	4
Error	2.55904078e+00	3.35413074e+00	1.39477491e+00	1.79452944e+00
view	5	6	7	8
Error	2.17249346e+00	2.10425711e+00	1.28227234e+00	1.40593469e+00
view	9	10	11	12
Error	1.28024423e+00	1.32076836e+00	1.32660282e+00	1.34940219e+00
view	13	14	15	
Error	1.35390007e+00	1.54767573e+00	1.66267991e+00	

6.15.1 Intrinsic Parameter K

610.5925	0	319.5
0	610.59251	239.5
0	0	1

6.15.2 Extrinsic Parameters

There are 15 rotation matrices for the 15 frames used to calibrate the camera.

6.15.3 Rotation Matrix 1

0.9944153858813619	0.04644720256834592	0.09476654312571038
0.06183190592599129	0.984102379779916	0.1664912055367049
0.08552692986411618	0.1714210123791159	0.9814784667953432

6.15.4 Rotation Matrix 2

0.9877072850168229	0.02189517931141388	0.1547737711875546
0.04214306369463074	0.9907773096138155	0.1287799865539668
0.150526679718669	0.1337195717811369	0.9795206964712602

6.15.5 Rotation Matrix 3

0.9785785947648702	0.01139635247293982	0.2055579164574416
0.02368345942061683	0.9856061664806332	0.1673904965797713
0.2045067911290087	0.1686730794930328	0.9642231923348727

6.15.6 Rotation Matrix 4

0.9889353151907873	0.03763356515977519	0.1434944498643178
0.01654880806631006	0.9892358932535118	0.1453907990572682
0.1474214343984032	0.1414074335821547	0.9789131005393819

6.15.7 Rotation Matrix 5

0.9932638515409313	0.03054604568229187	0.1117759379976311
0.01435745801753814	0.9896381475906408	0.1428642720649206
0.1149816708060444	0.1402970987816226	0.9834103616761981

6.15.8 Rotation Matrix 6

0.9889313685214007	0.04631375490558493	0.1409602229741957
0.02677026419461661	0.9901388915865775	0.1375075573292396
0.1459386902412791	0.1322119944416886	0.9804192405376442

6.15.9 Rotation Matrix 7

0.9860060464987002	0.0514562035824	0.1585696546659849
0.02715618304314679	0.9880439617364435	0.151761890468854
0.1644828805393747	0.1453319950631654	0.9756146745618527

6.15.10 Rotation Matrix 8

0.9884177304001679	0.04903547399095185	0.1436172431188668
0.02453856250354929	0.9855470760410654	0.1676150943595648
0.1497606396248374	0.1621495704508313	0.9753354641464497

6.15.11 Rotation Matrix 9

0.9858948001064214	0.04865544162448861	0.1601377254848005
0.0254425131766876	0.98926018164094	0.1439339138041776
0.165421043541544	0.1378293909877728	0.9765443857467853

6.15.12 Rotation Matrix 10

0.9864359650763496	0.04919714638842972	0.1566005350920815
0.02520419825167085	0.9881114263639688	0.1516593468252245
0.1621999851861316	0.1456552432156106	0.9759486230993003

6.15.13 Rotation Matrix 11

0.9905671015421	0.04655920125705018	0.128876134799226
0.02617475386368812	0.9874790952590239	0.1555632305096387
0.1345053887495148	0.1507225172451851	0.9793829808571398

6.15.14 Rotation Matrix 12

0.9861447970862782	0.0515363816618411	0.157678281779287
0.02753010035394438	0.9881802201124655	0.1508043306837737
0.1635864687379887	0.1443740071608607	0.9759075844065107

6.15.15 Rotation Matrix 13

0.9850143337507793	0.05407819465414048	0.1637751848371947
0.0290230116137913	0.9880035153001969	0.1516796576714206
0.1700130203907164	0.14465338785318	0.9747671364383512

6.15.16 Rotation Matrix 14

0.9870972564948877	0.05471295201660221	0.150484215457619
0.03136552065742539	0.9876730612924687	0.1533562131478606
0.1570197768886287	0.146657481496146	0.9766454693424083

6.15.17 Rotation Matrix 15

0.9888288940751532	0.05372955742912307	0.1390343587052494
0.03184827615672366	0.9873905459629507	0.1550664278586154
0.1456128618905434	0.1489061597163014	0.9780714953675875

6.16 Output Image

The screenshot of the calibration video is as follows