

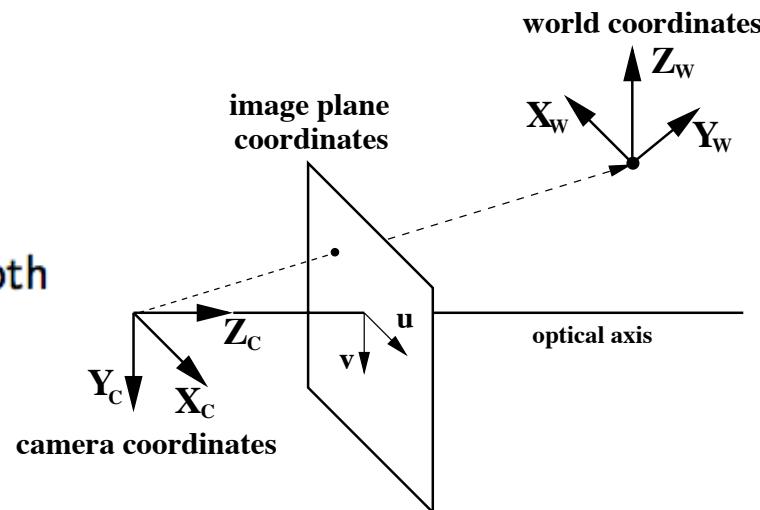
# Camera Calibration

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# The 3x4 projection matrix $P$

$$\lambda \begin{pmatrix} u \\ v \\ 1 \end{pmatrix} = \begin{pmatrix} f & 0 & u_o \\ 0 & f & v_o \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} R & t \end{pmatrix} \begin{pmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{pmatrix} = P \begin{pmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{pmatrix}$$

$\lambda$  is the unknown depth

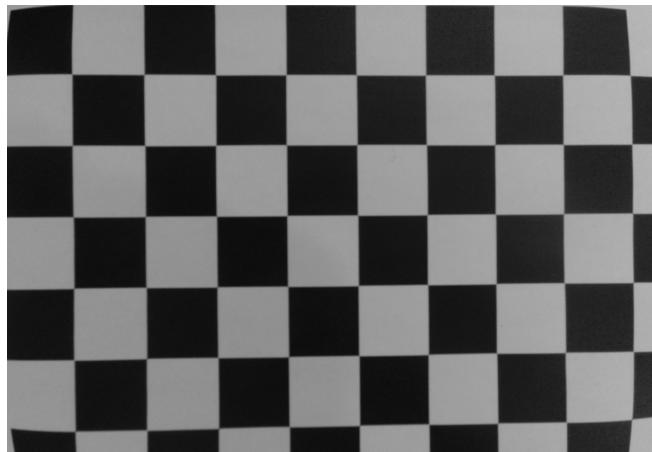


Cameras with large field of view  
have radial distortions

$$u^{dist} = u(1 + k_1 r + k_2 r^2 + k_3 r^3 + \dots)$$

$$v^{dist} = v(1 + k_1 r + k_2 r^2 + k_3 r^3 + \dots)$$

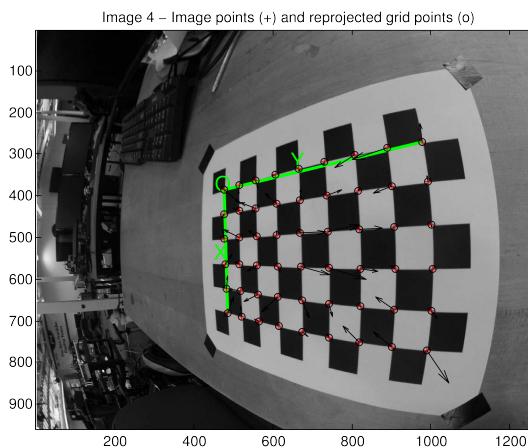
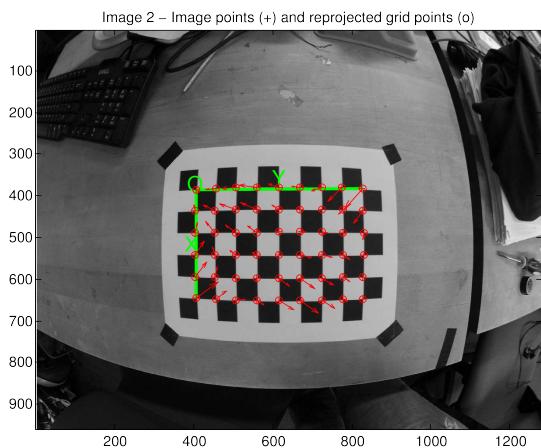
where  $r^2 = u^2 + v^2$



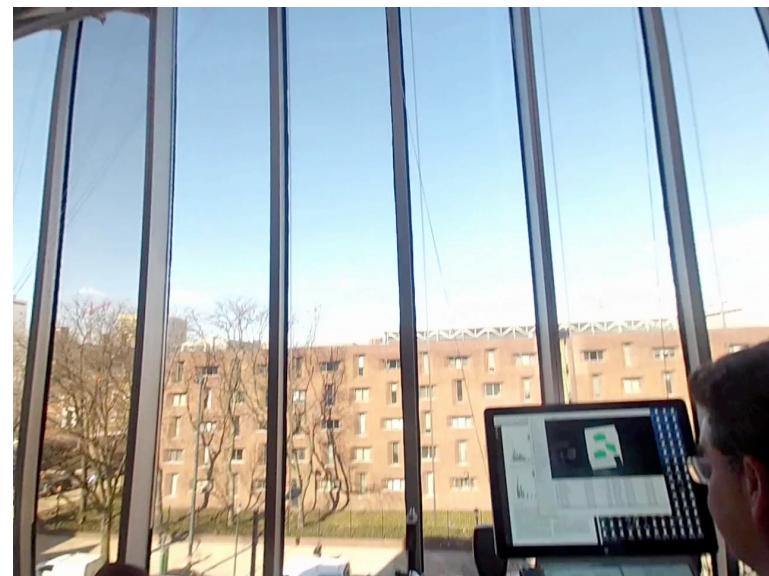
# A procedure called **calibration**

Estimates the *intrinsic parameters*

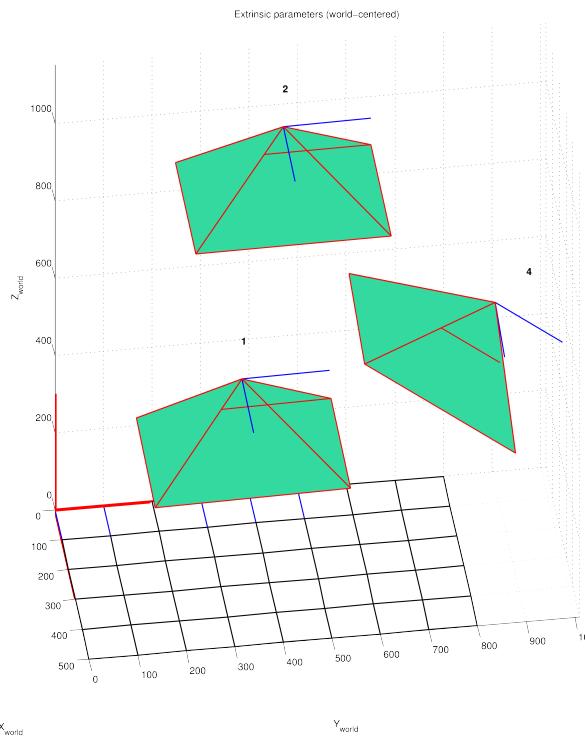
- $f$  focal length
- $(u_o, v_o)$  image center
- $k_1, k_2, \dots$  radial distortion parameters



As a result of the calibration we have undistorted images and video



..as well as the poses of the camera and the projection rays in world coordinates

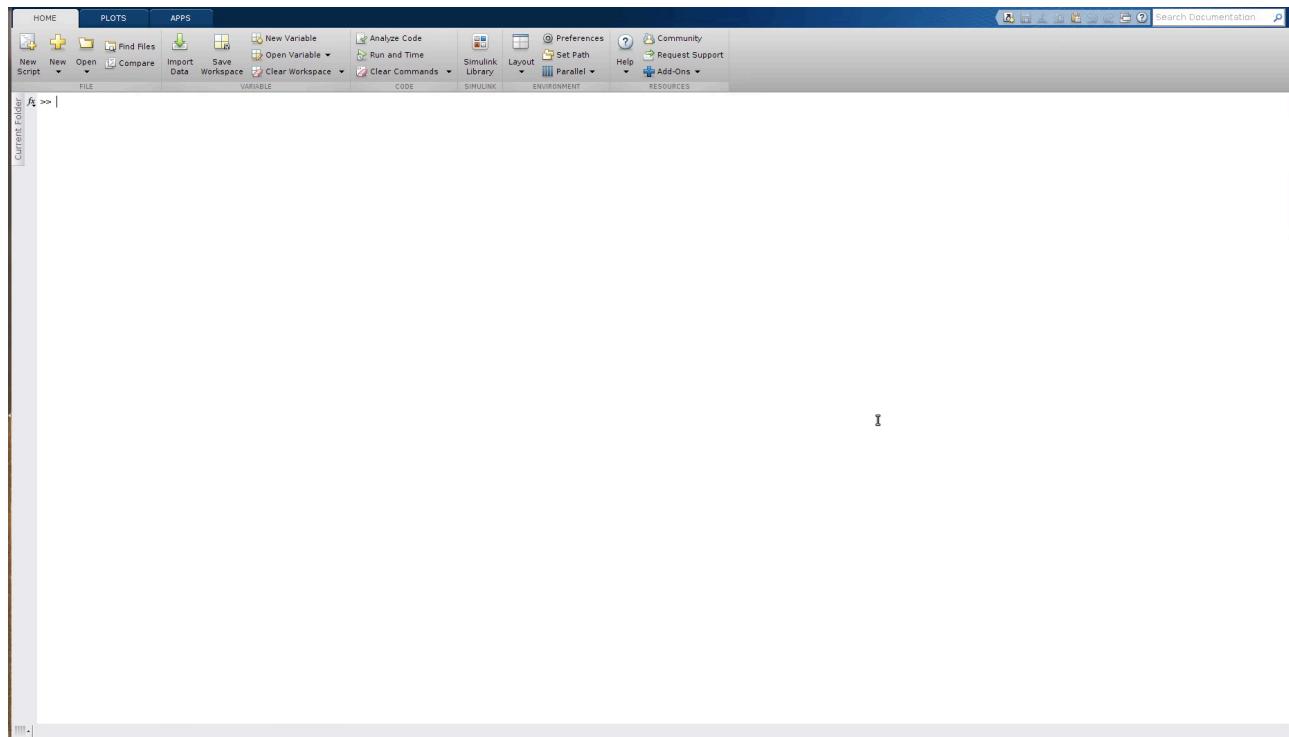


$$\begin{pmatrix} X_w \\ Y_w \\ Z_w \end{pmatrix} = \boxed{-R^T T} + \lambda \boxed{R^T K^{-1}} \begin{pmatrix} u \\ v \\ 1 \end{pmatrix}$$

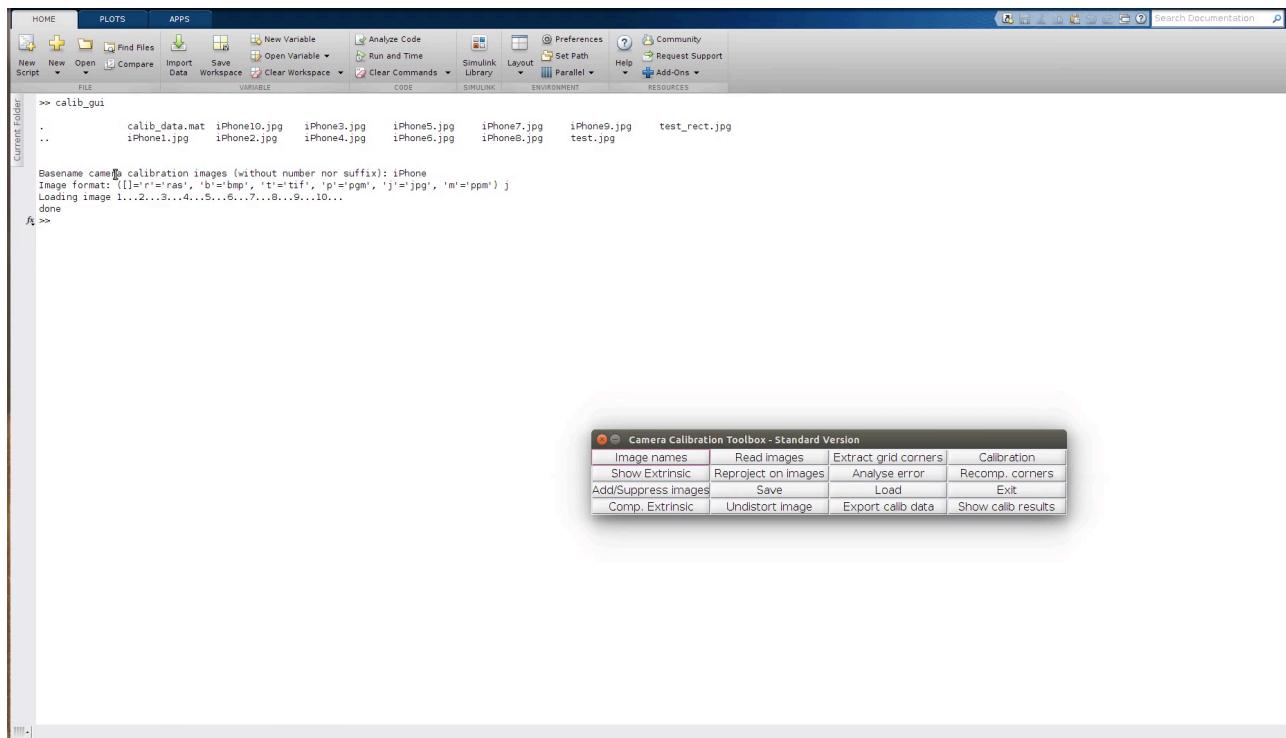
known

We will return later on the specifics of calibration....

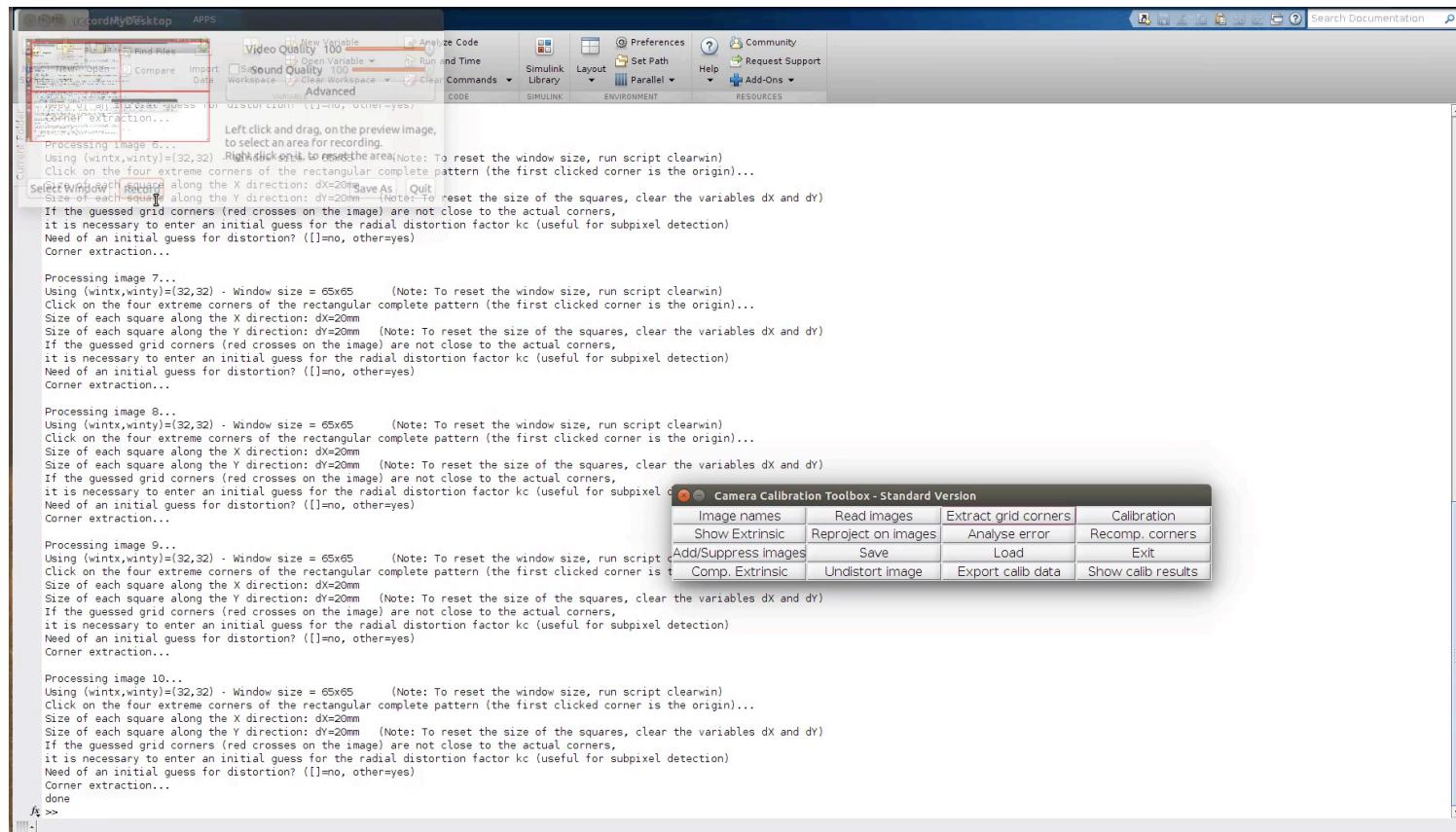
# How we calibrate in Matlab?



# Extracting corners of the checkerboard



# Extrinsic parameter results (R,T)



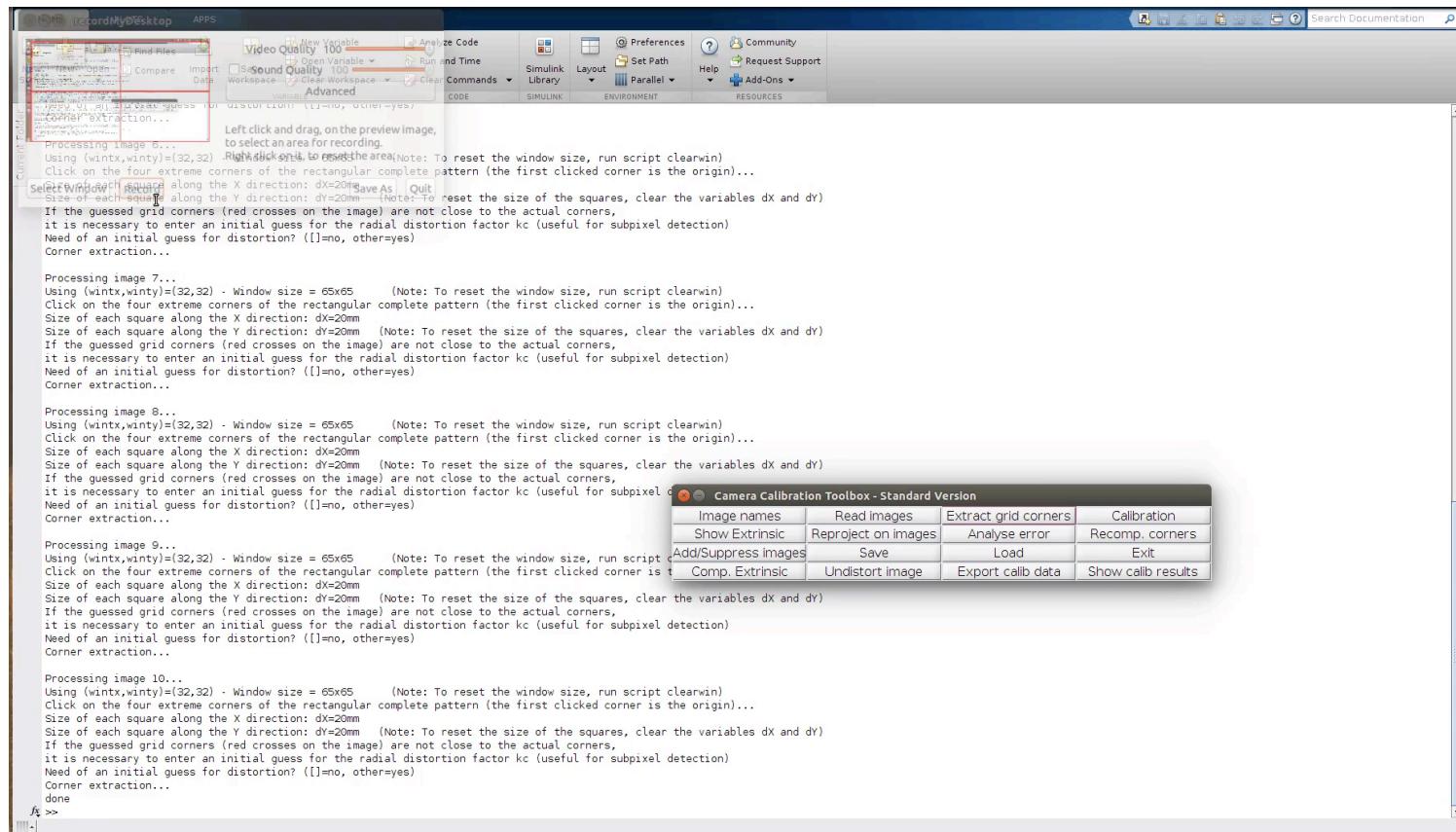
# Extrinsic parameter results (R,T)

Calibration results after optimization (with uncertainties):

```
Focal Length:      fc = [ 3460.99207  3450.27097 ] +/- [ 10.58701  10.40724 ]
Principal point: cc = [ 2029.63006  1511.12039 ] +/- [ 7.55158  7.25607 ]
Skew:             alpha_c = [ 0.00000 ] +/- [ 0.00000 ] => angle of pixel axes = 90.00000 +/- 0.00000 degrees
Distortion:       kc = [ 0.07078  -0.07501  -0.00072  0.00094  0.00000 ] +/- [ 0.00520  0.01581  0.00073
Pixel error:      err = [ 0.54275  0.61021 ]                                     0.00085  0.00000 ]
```

Note: The numerical errors are approximately three times the standard deviations (for reference).

# Extrinsic parameter results (R,T)



# Reproject undistorted coordinates

