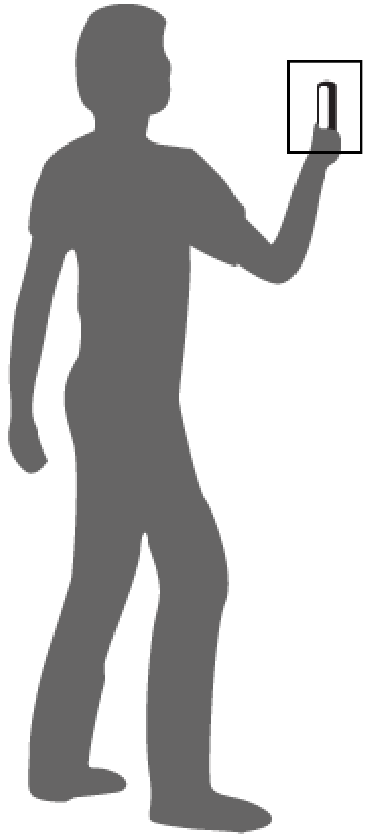
Multiview Camera Calibration

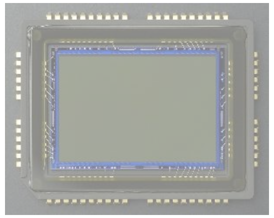
Hyun Soo Park

Camera Intrinsic Parameter



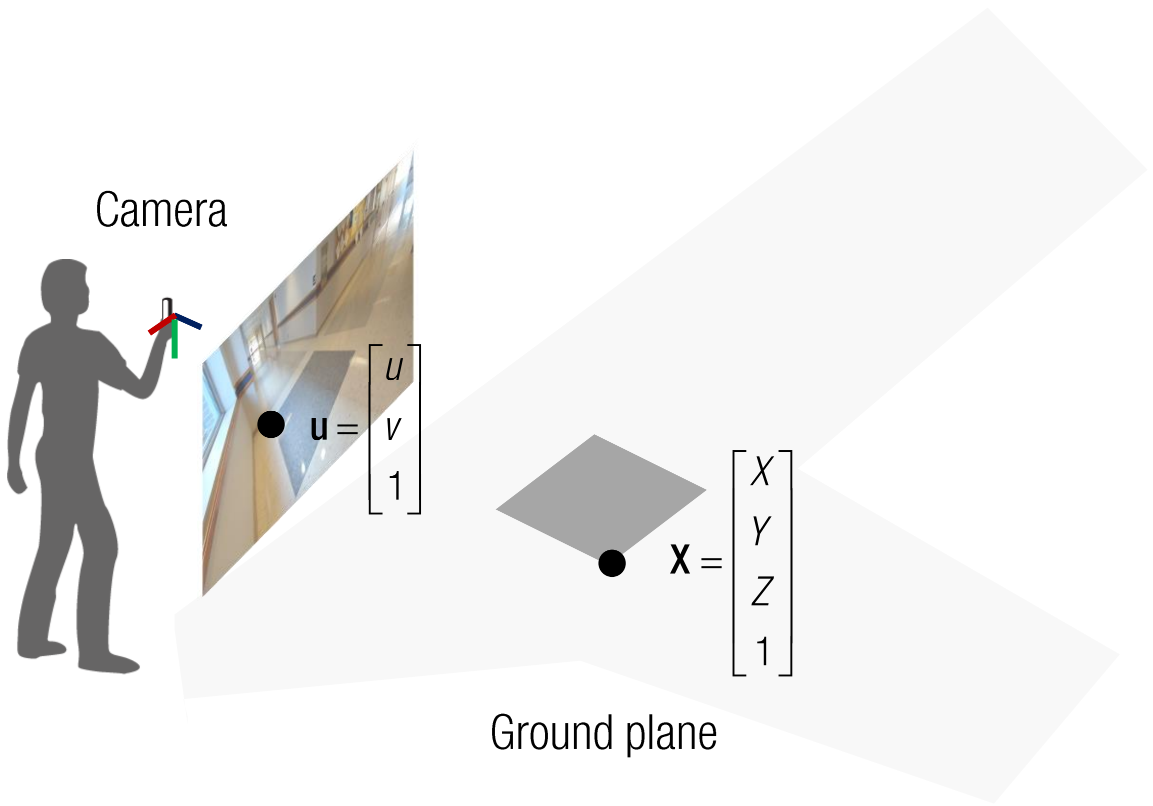
Pixel space — Metric space

$$\lambda \begin{bmatrix} u_{\text{img}} \\ v_{\text{img}} \\ 1 \end{bmatrix} = \underbrace{\begin{bmatrix} f_x & & p_x \\ & f_y & p_y \\ & & 1 \end{bmatrix}}_{\mathbf{K}} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

 + 

Camera intrinsic parameter
: metric space to pixel space

Camera Calibration in Pixel Space



$$\lambda \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix} \begin{bmatrix} \mathbf{R} & \mathbf{t} \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

# of unknowns: 3 (**K**) + 6F (**R** and **t**) + 3P (**X**)

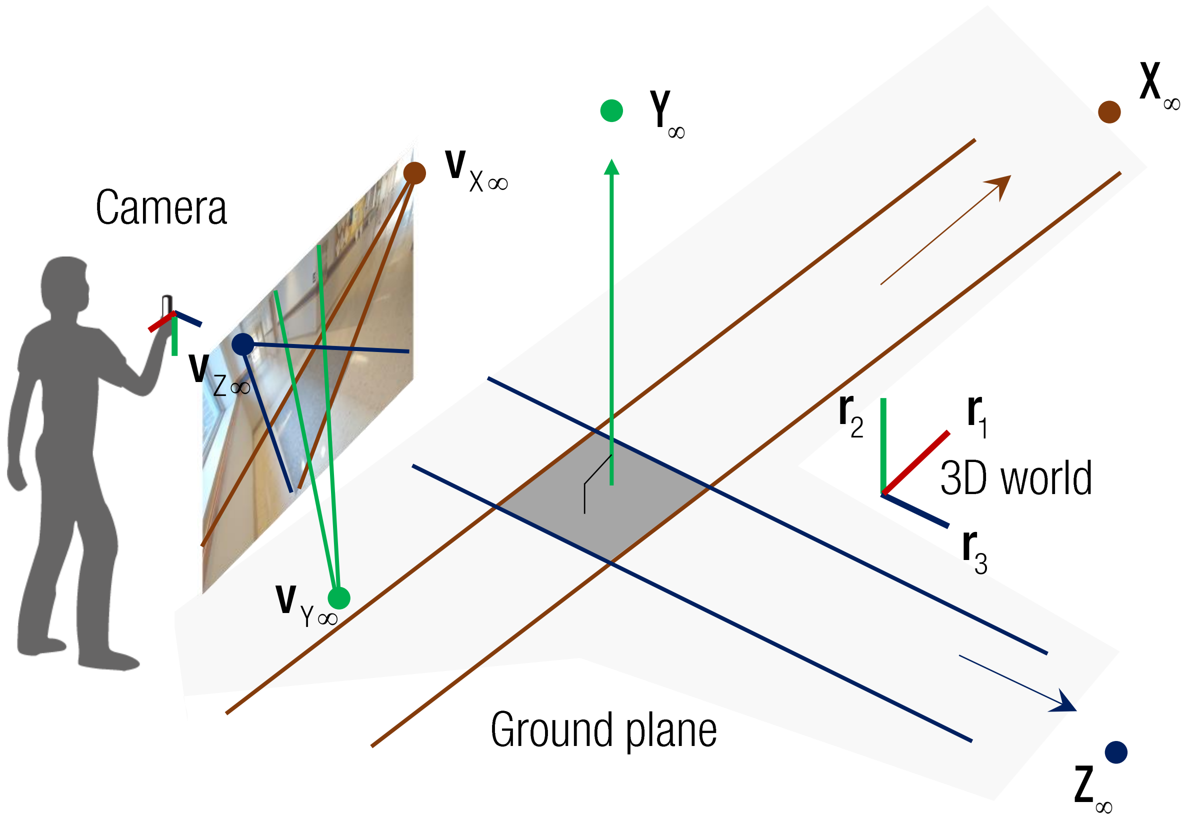
# of equations: 2P

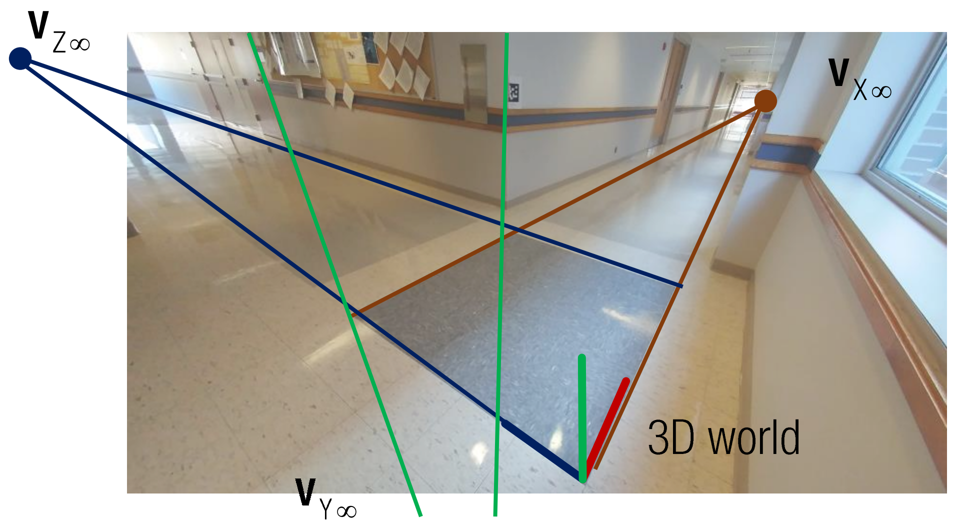
where F is # of images and P is # of points.

# of unknowns > # of equations

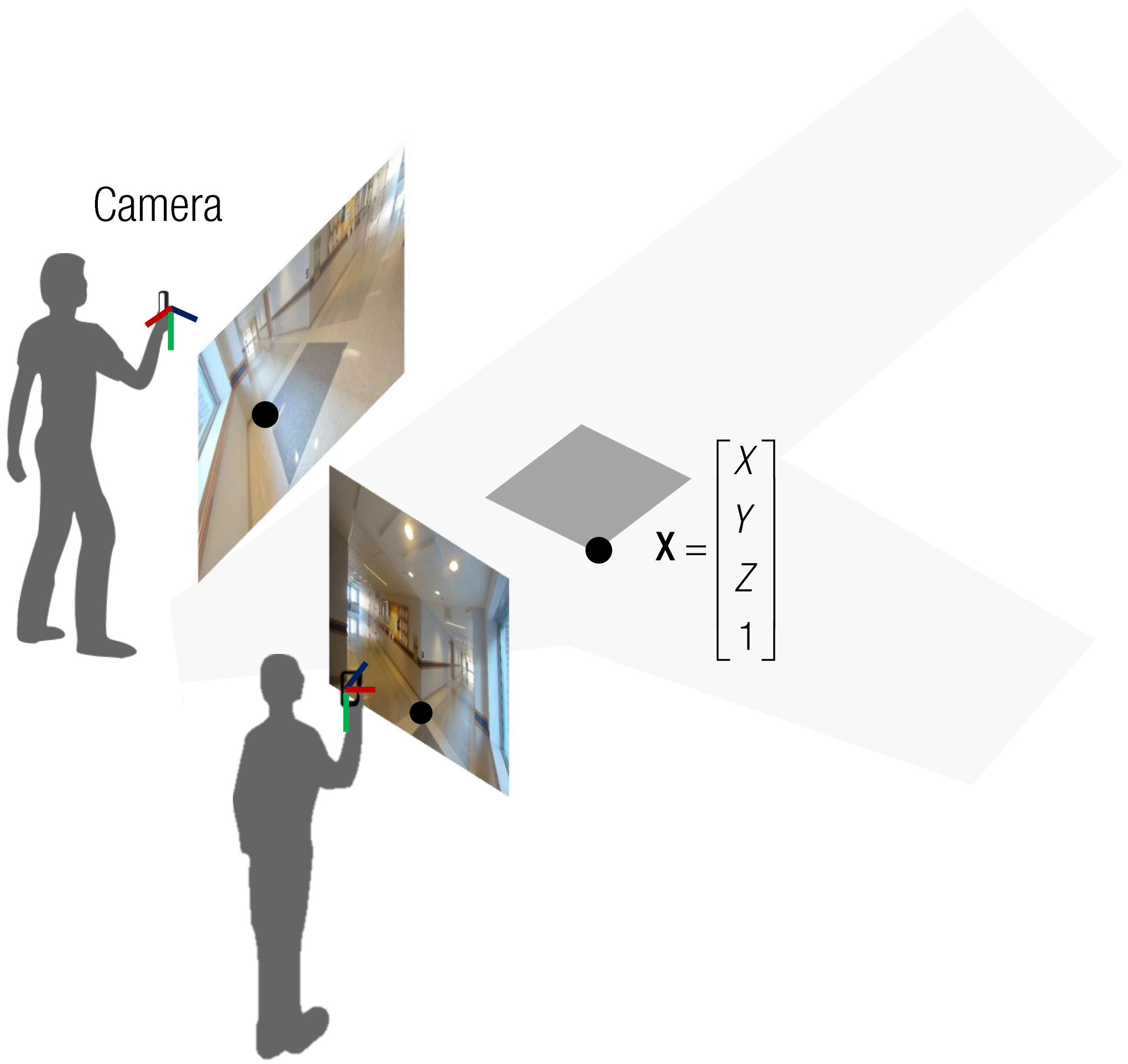
What do we know about the scene?

Camera Calibration via Vanishing Points

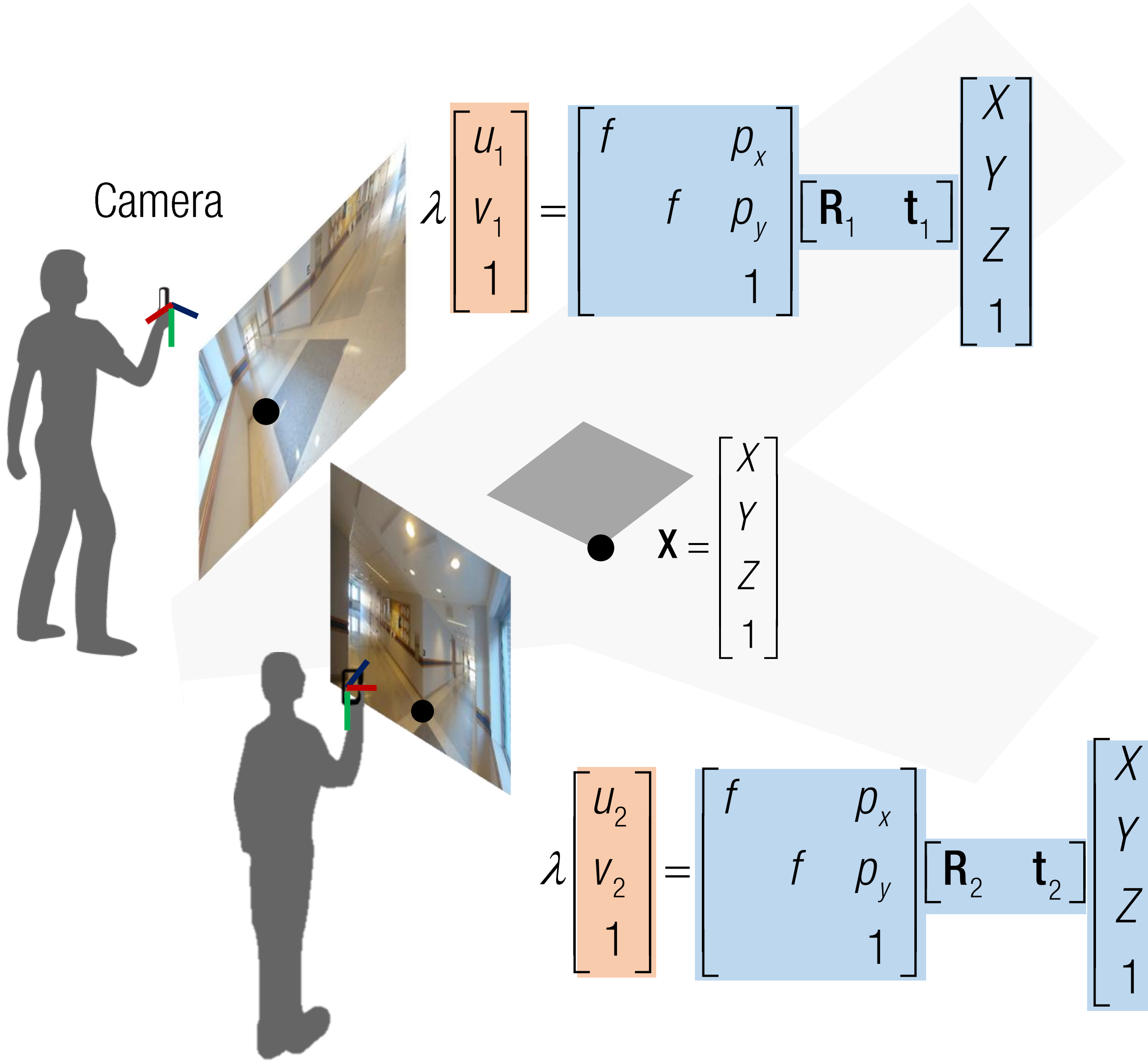




Multiview Camera Calibration



Multiview Camera Calibration



$$\lambda \begin{bmatrix} u_1 \\ v_1 \\ 1 \end{bmatrix} = \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix} \begin{bmatrix} \mathbf{R}_1 & \mathbf{t}_1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

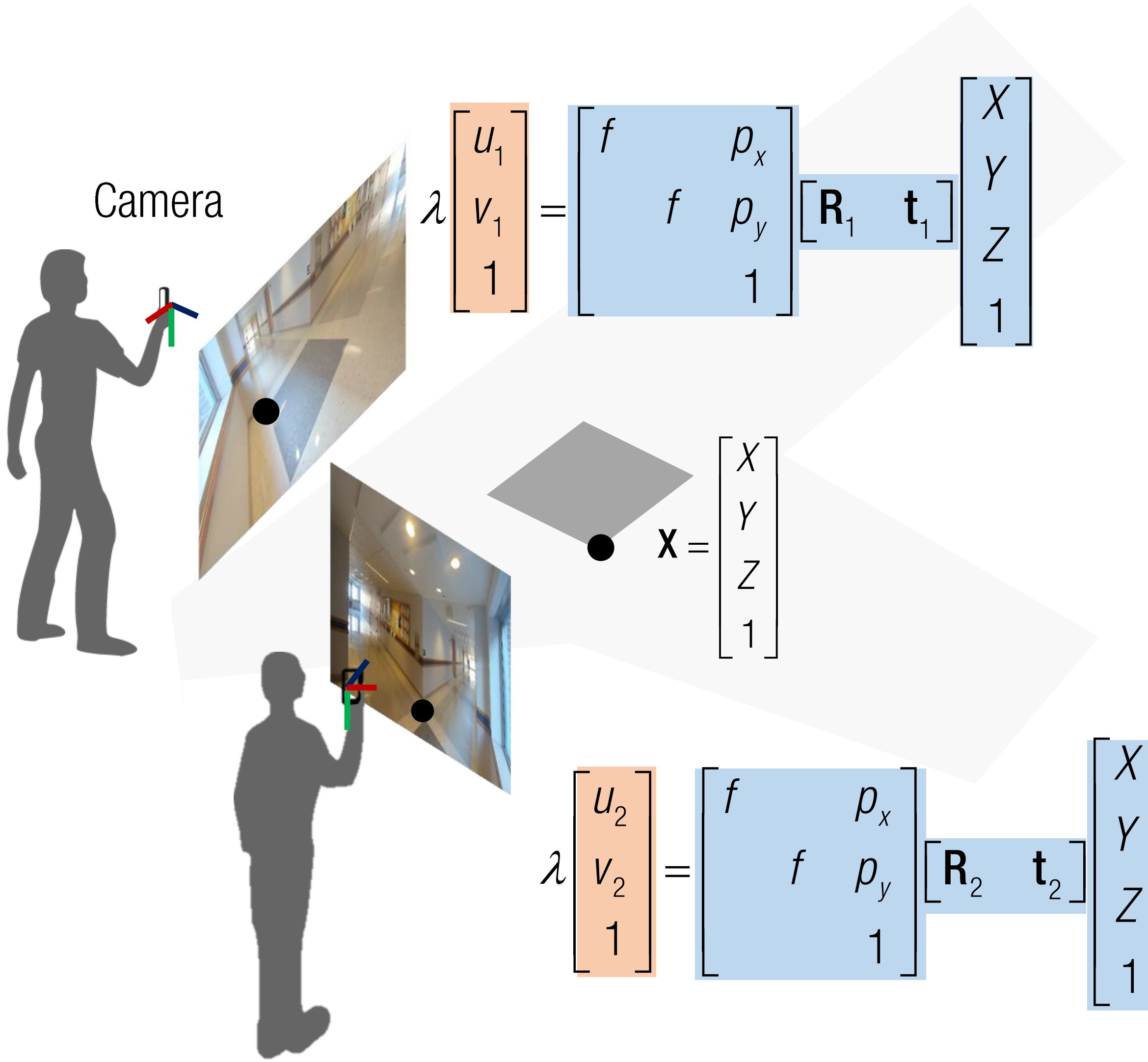
$$\mathbf{X} = \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

$$\lambda \begin{bmatrix} u_2 \\ v_2 \\ 1 \end{bmatrix} = \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix} \begin{bmatrix} \mathbf{R}_2 & \mathbf{t}_2 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

: Knowns

: Unknowns

Multiview Camera Calibration



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# of unknowns:

n: the number of images

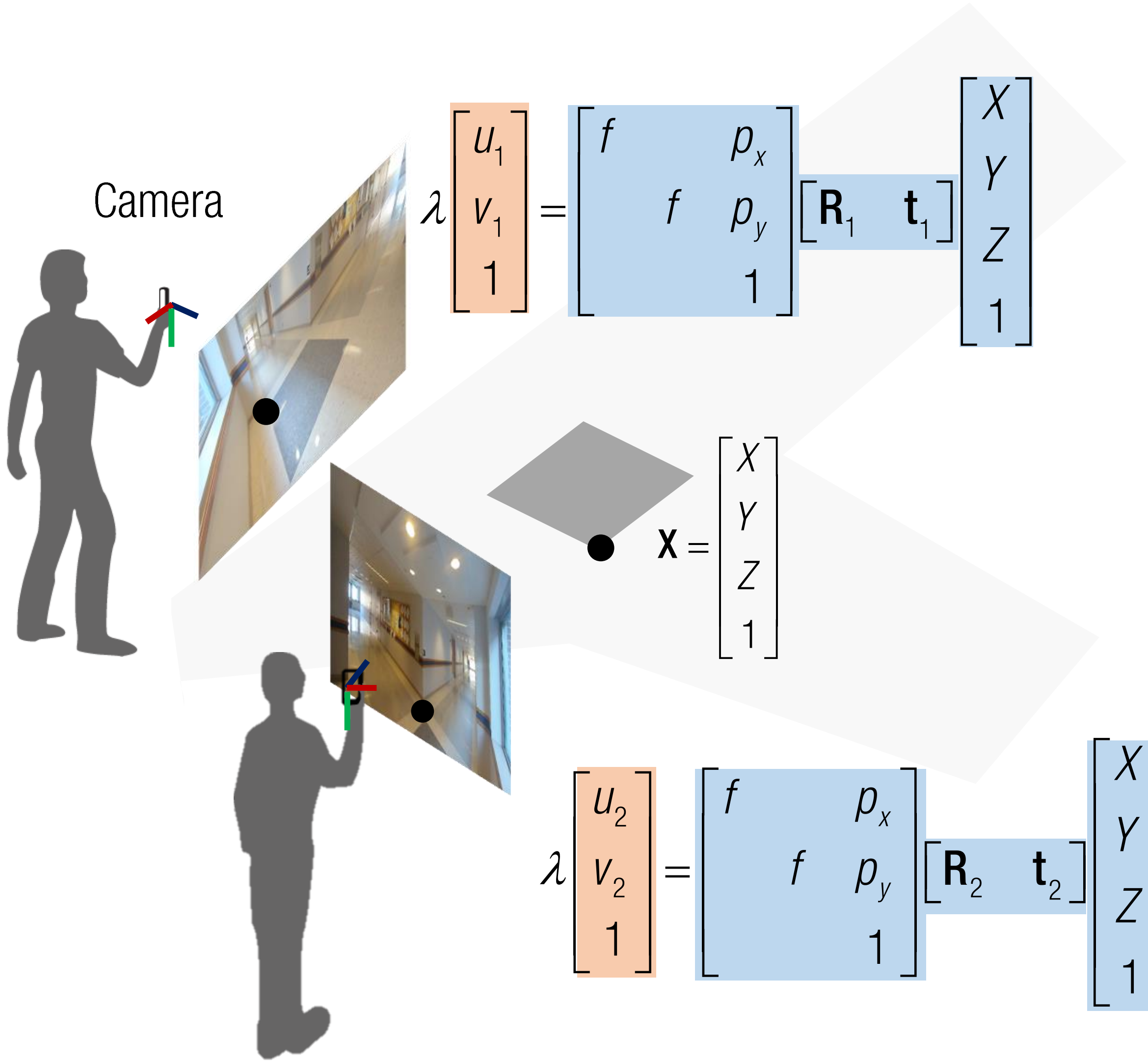
p: the number of points

# of equations:

: Knowns

: Unknowns

Multiview Camera Calibration



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# of unknowns: 3 (**K**) + 6n (**R** and **t**) + 3p (**X**)

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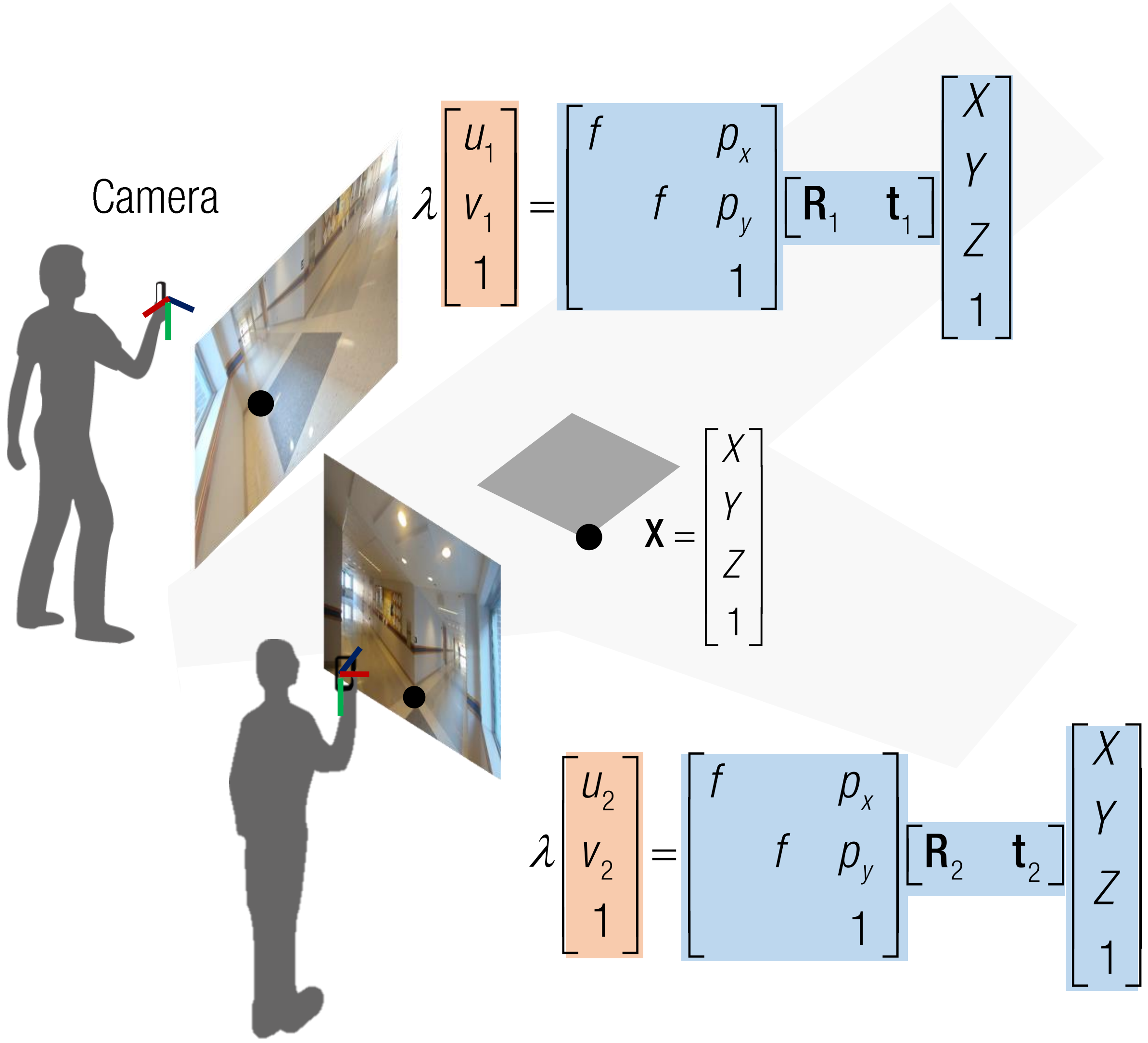
# of equations:

: Knowns

: Unknowns

Multiview Camera Calibration



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# of unknowns: 3 (**K**) + 6n (**R** and **t**) + 3p (**X**)

n: the number of images

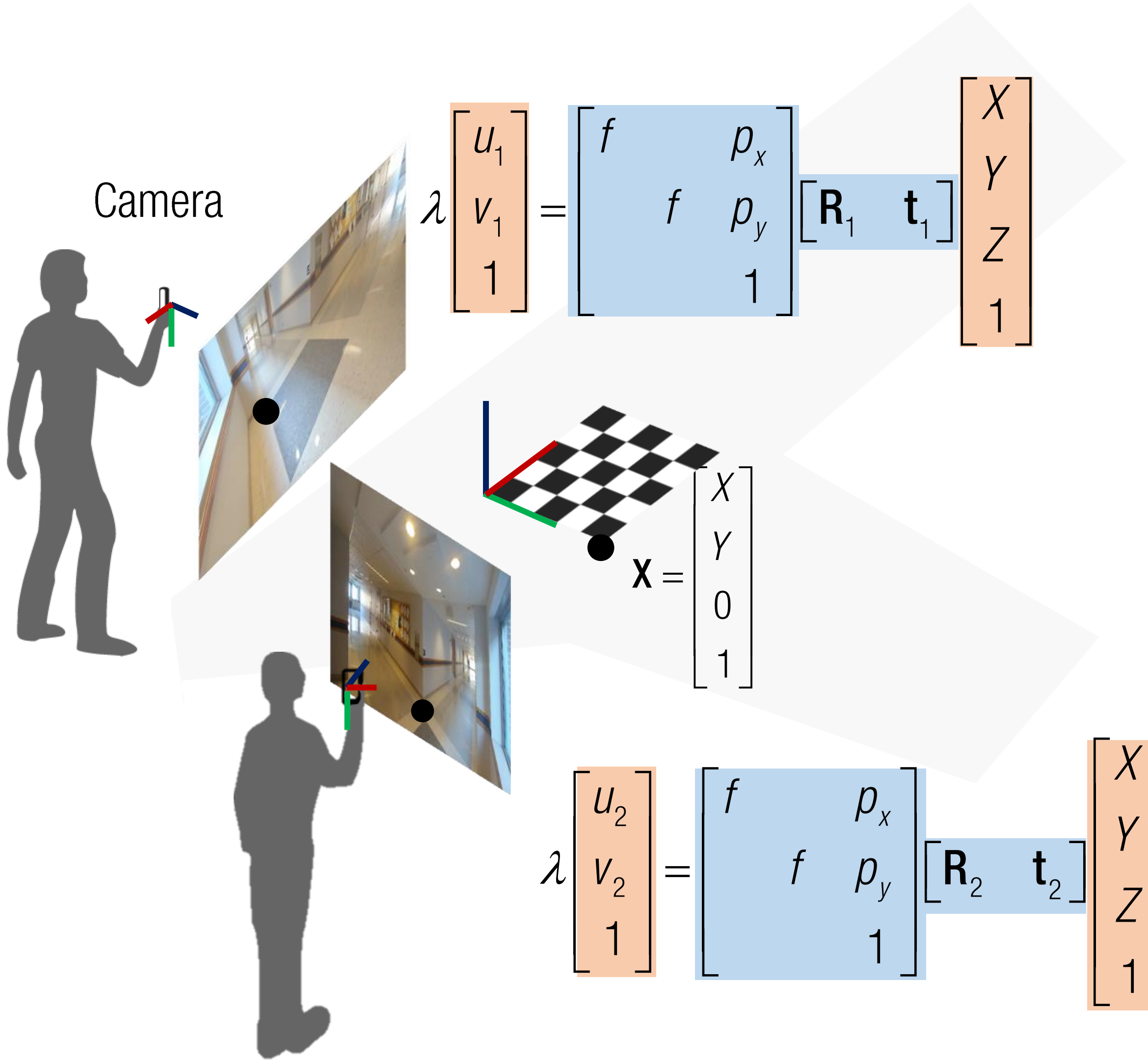
p: the number of points

# of equations: 2np

: Knowns

: Unknowns

Insight: Known Common 3D Points



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# of unknowns: 3 (**K**) + 6n (**R** and **t**)

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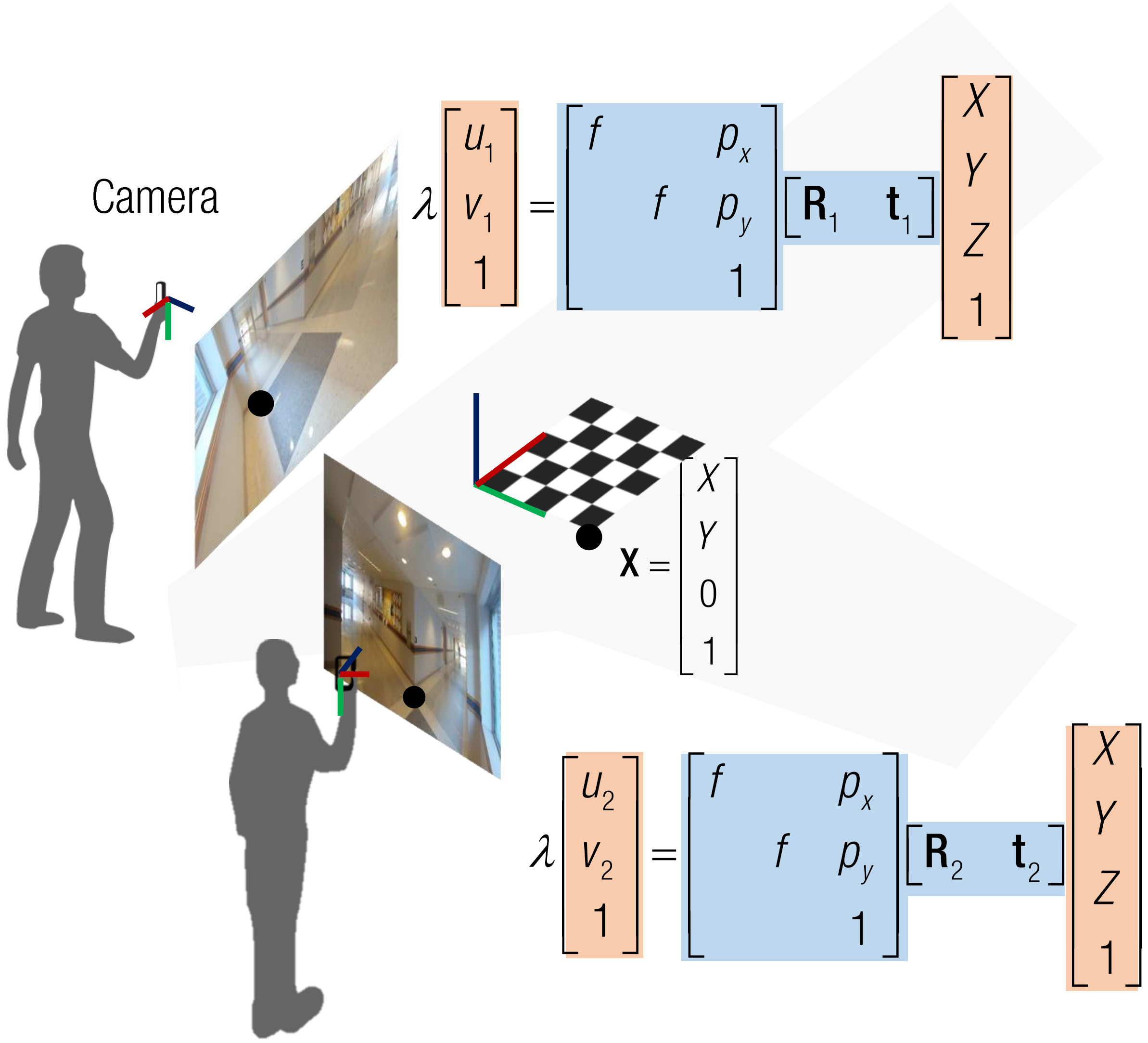
p: the number of points

# of equations: 2np

: Knowns

: Unknowns

Insight: Known Common 3D Points



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# of unknowns: 3 (**K**) + 6*n* (**R** and **t**)

n: the number of images

p: the number of points

# of equations: 2*np*

We can solve for **K**, **R**, **t** if $3 + 6n < 2\ nm$

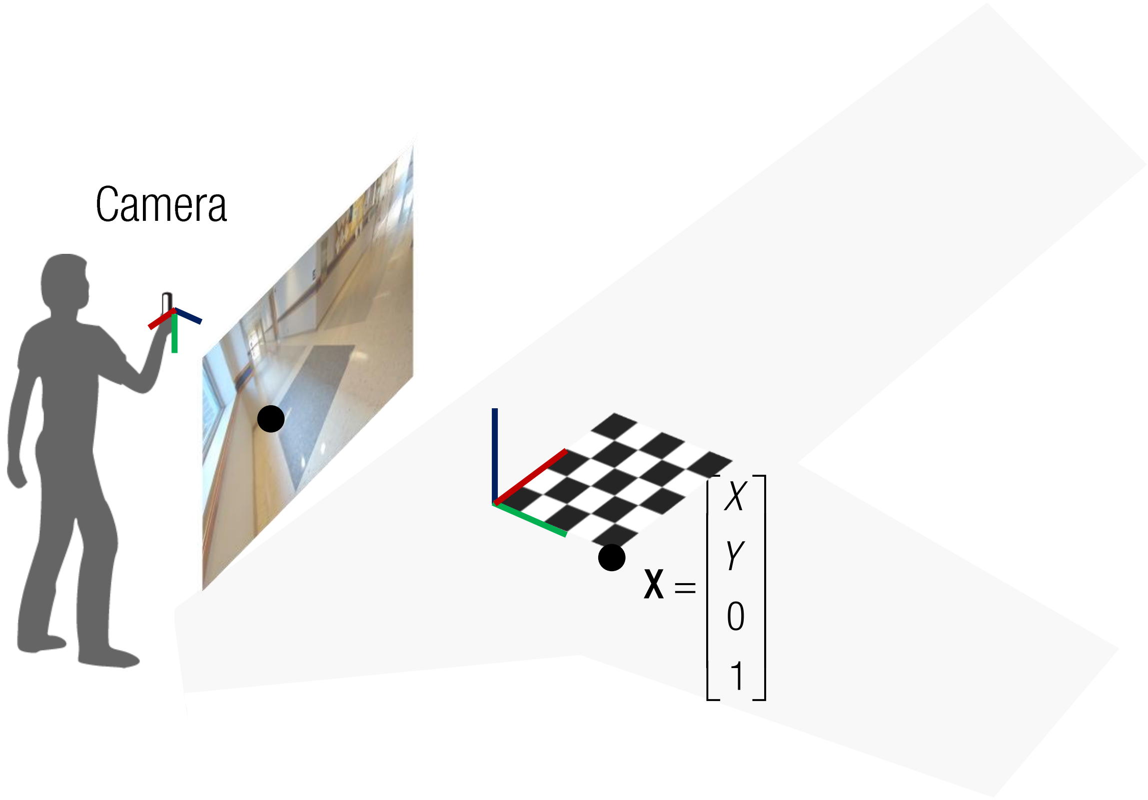
: Knowns

: Unknowns

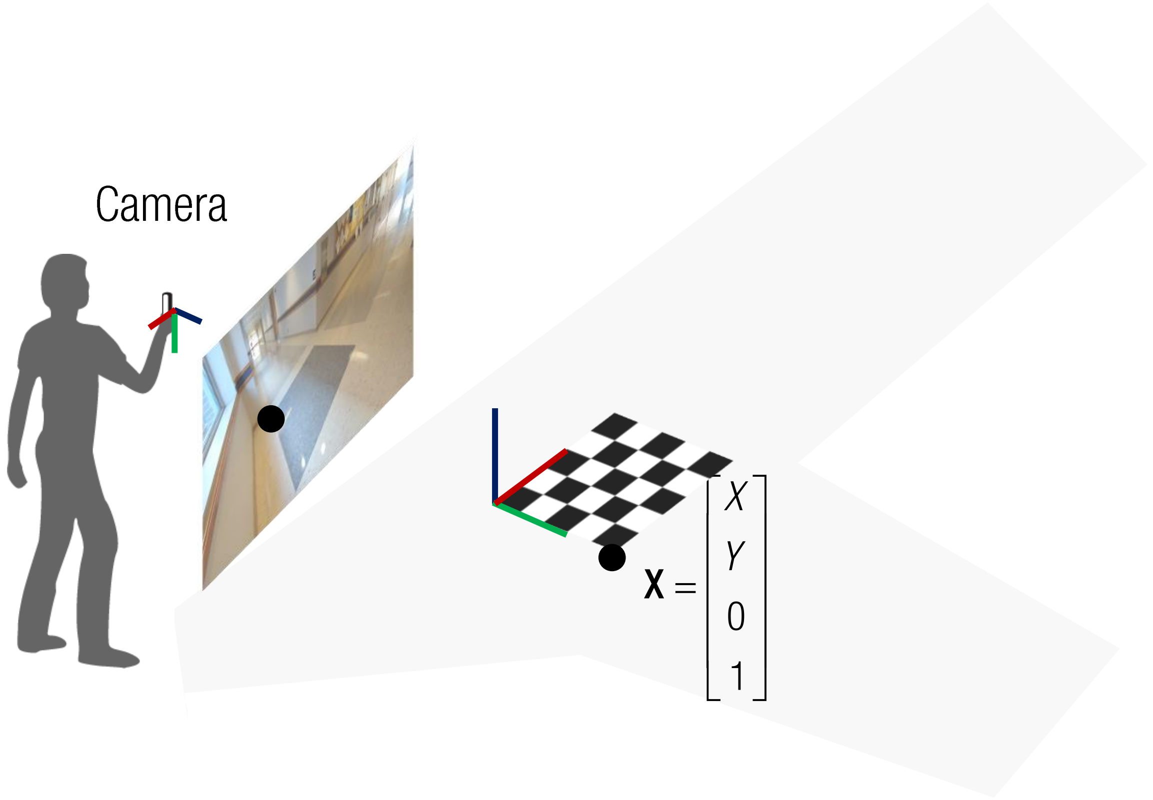
Homography

Points in 2D plane are mapped to an image with homography:

$$\lambda \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix} \begin{bmatrix} \mathbf{r}_1 & \mathbf{r}_2 & \mathbf{r}_3 & \mathbf{t} \end{bmatrix} \begin{bmatrix} X \\ Y \\ 0 \\ 1 \end{bmatrix}$$



Homography



$$\mathbf{X} = \begin{bmatrix} X \\ Y \\ 0 \\ 1 \end{bmatrix}$$

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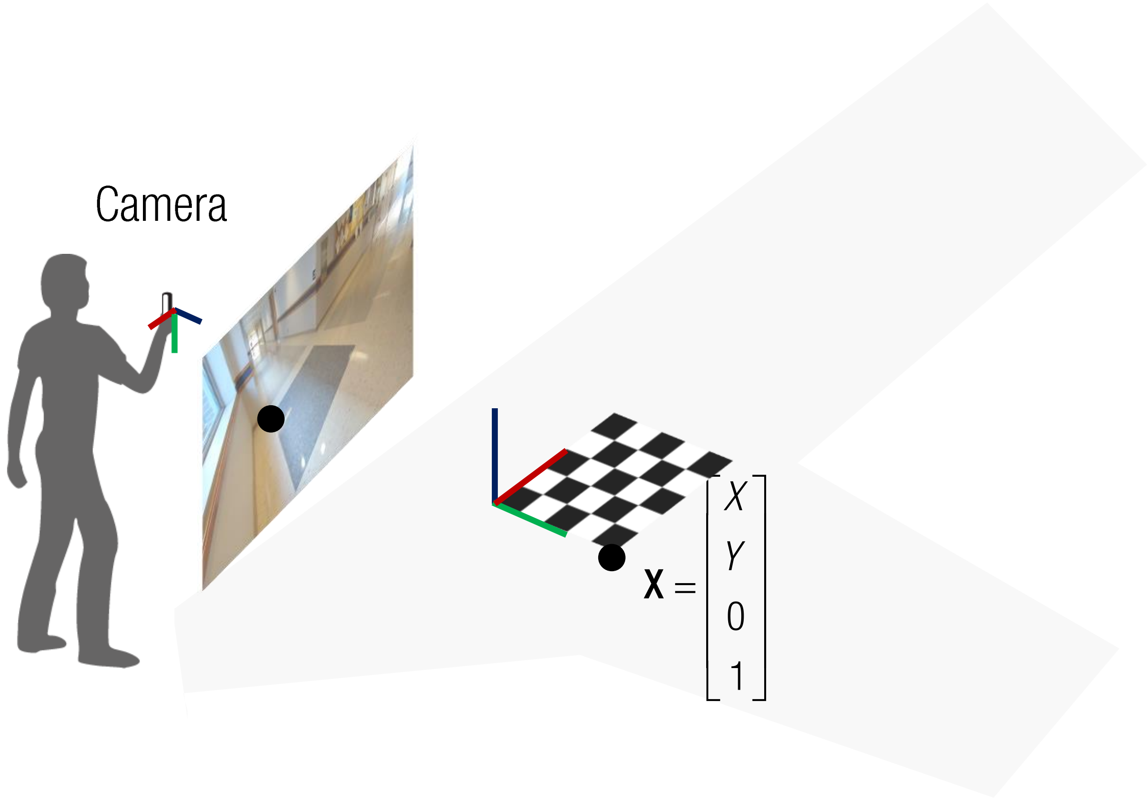
$$= \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix} \begin{bmatrix} \mathbf{r}_1 & \mathbf{r}_2 & \mathbf{t} \end{bmatrix} \begin{bmatrix} X \\ Y \\ 1 \end{bmatrix}$$

Homography



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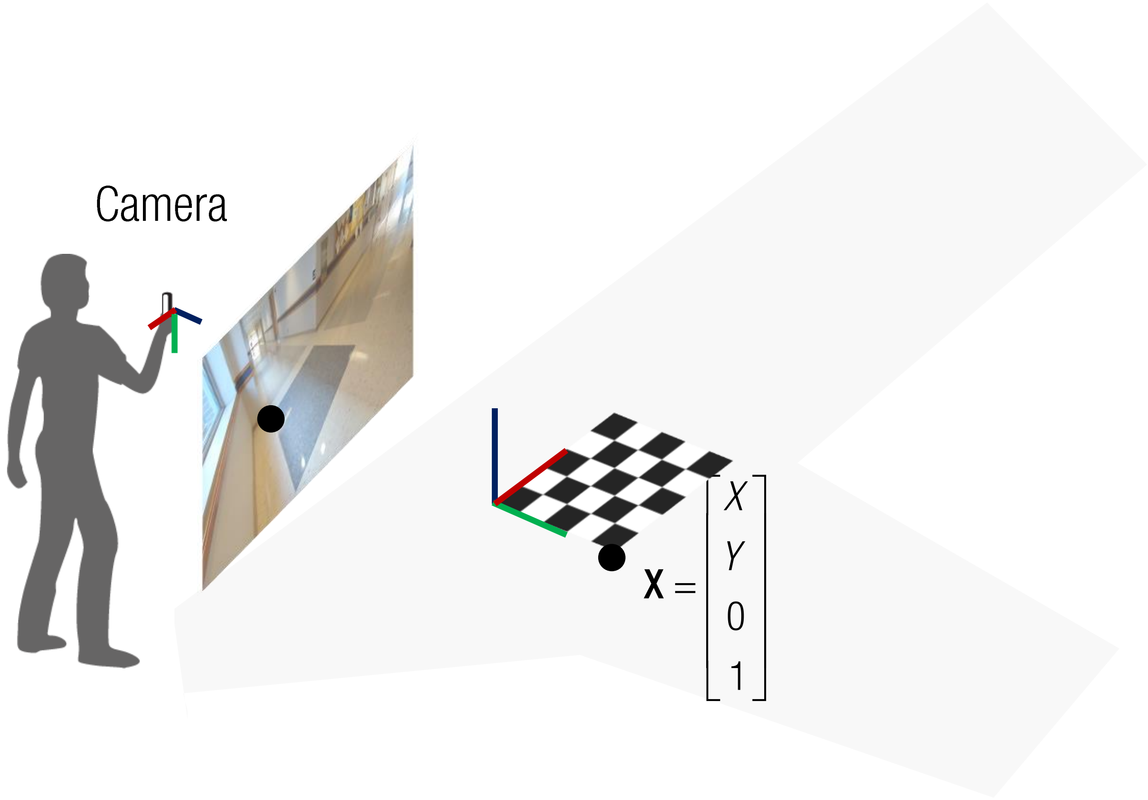
$$= \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix} \begin{bmatrix} \mathbf{r}_1 & \mathbf{r}_2 & \mathbf{t} \end{bmatrix} \begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} = \mathbf{H} \begin{bmatrix} X \\ Y \\ 1 \end{bmatrix}$$

Homography



$$\mathbf{X} = \begin{bmatrix} X \\ Y \\ 0 \\ 1 \end{bmatrix}$$

Points in 2D plane are mapped to an image with homography:

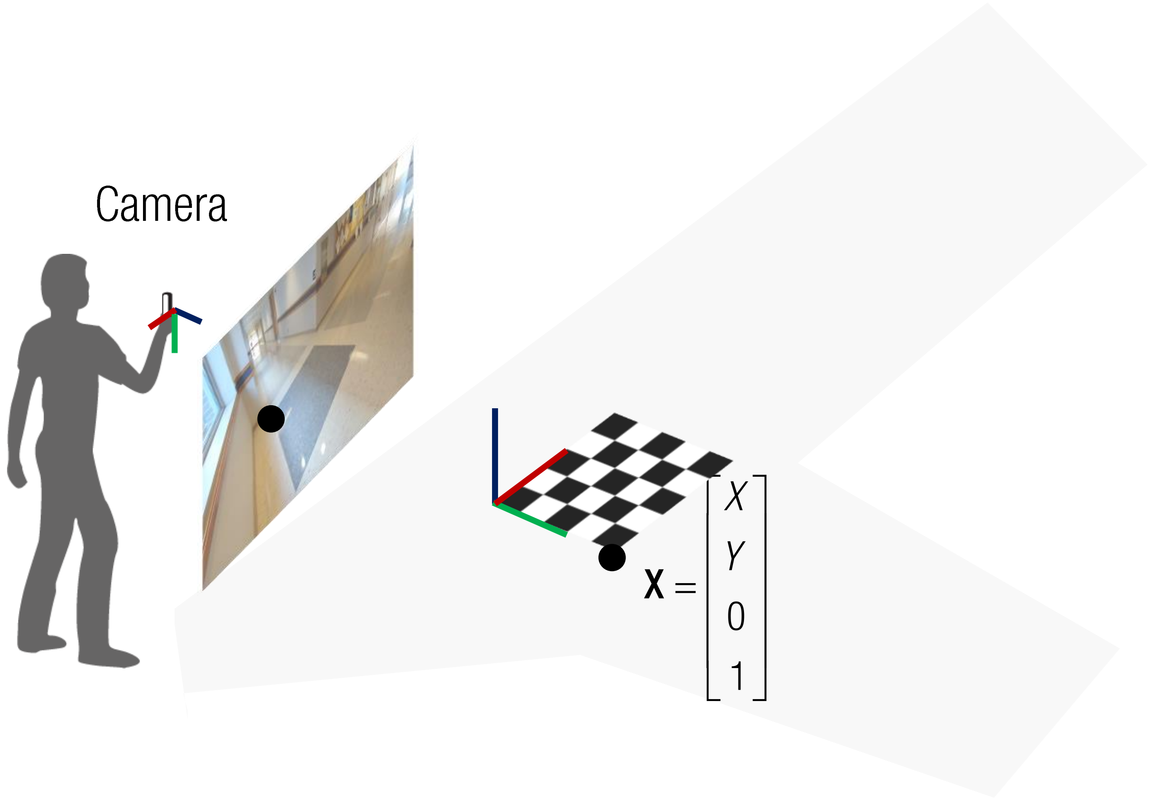
$$\lambda \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix} \begin{bmatrix} \mathbf{r}_1 & \mathbf{r}_2 & \mathbf{r}_3 & \mathbf{t} \end{bmatrix} \begin{bmatrix} X \\ Y \\ 0 \\ 1 \end{bmatrix}$$

$$= \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix} \begin{bmatrix} \mathbf{r}_1 & \mathbf{r}_2 & \mathbf{t} \end{bmatrix} \begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} = \mathbf{H} \begin{bmatrix} X \\ Y \\ 1 \end{bmatrix}$$

1. Compute homography

$$\lambda \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \mathbf{H} \begin{bmatrix} X \\ Y \\ 1 \end{bmatrix}$$

Homography

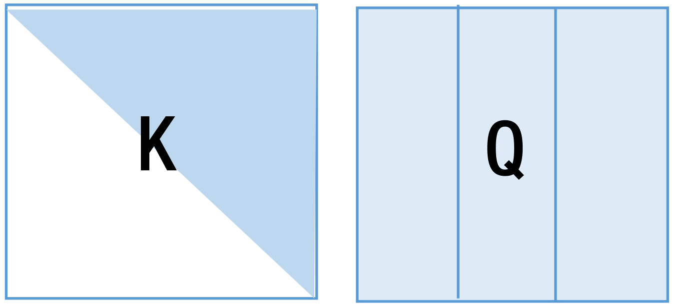


Points in 2D plane are mapped to an image with homography:

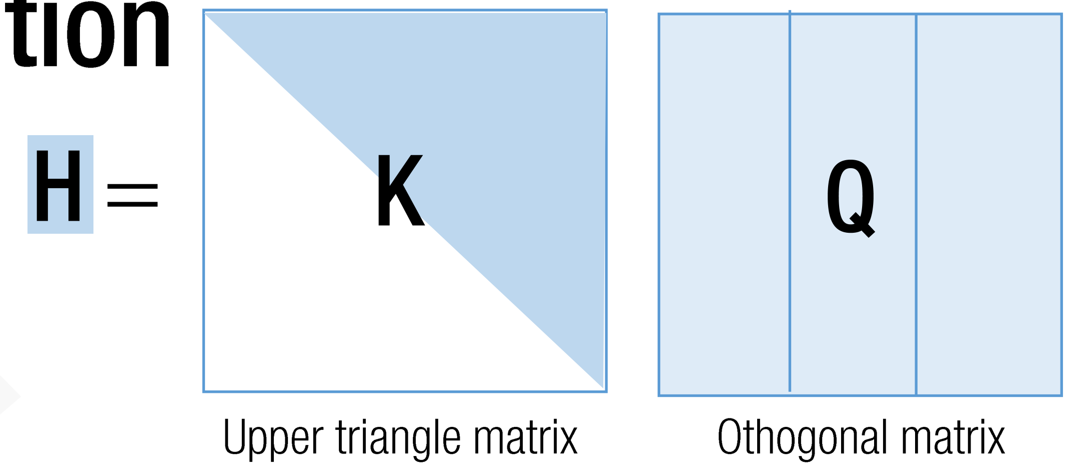
$$\lambda \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix} \begin{bmatrix} \mathbf{r}_1 & \mathbf{r}_2 & \mathbf{r}_3 & \mathbf{t} \end{bmatrix} \begin{bmatrix} X \\ Y \\ 0 \\ 1 \end{bmatrix}$$

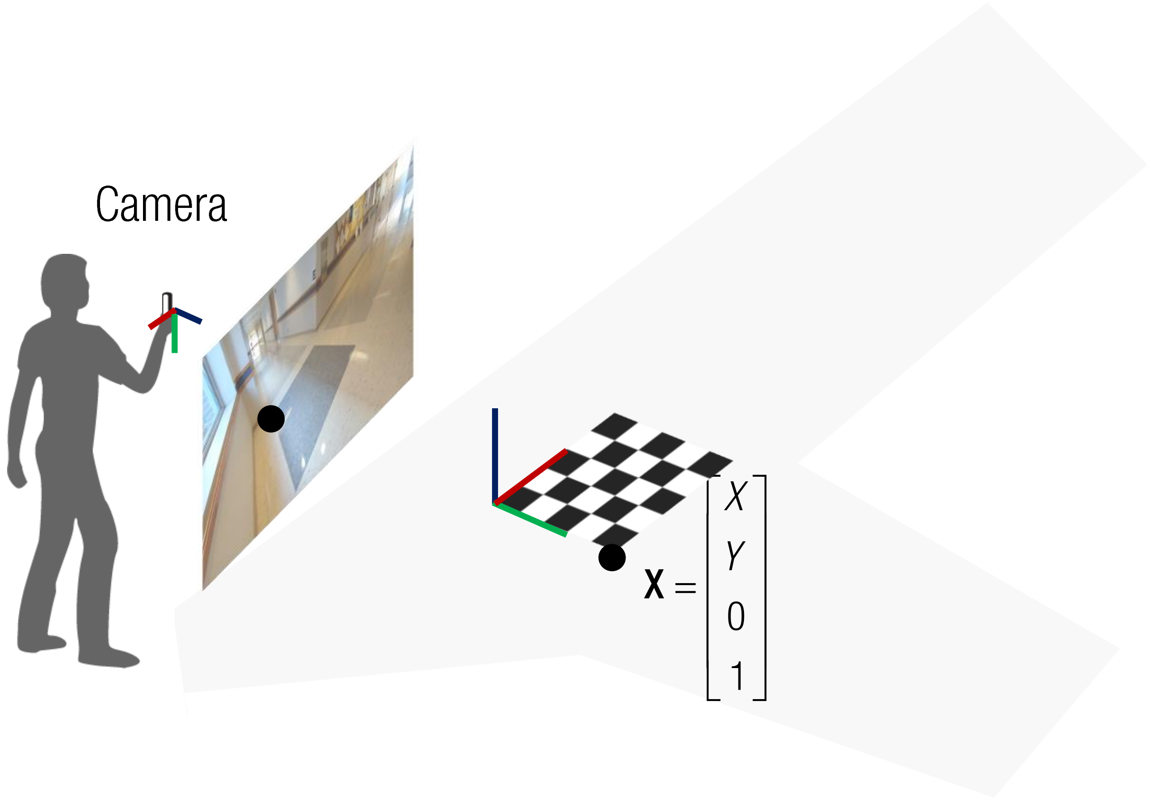
$$= \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix} \begin{bmatrix} \mathbf{r}_1 & \mathbf{r}_2 & \mathbf{t} \end{bmatrix} \begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} = \mathbf{H} \begin{bmatrix} X \\ Y \\ 1 \end{bmatrix}$$

H =

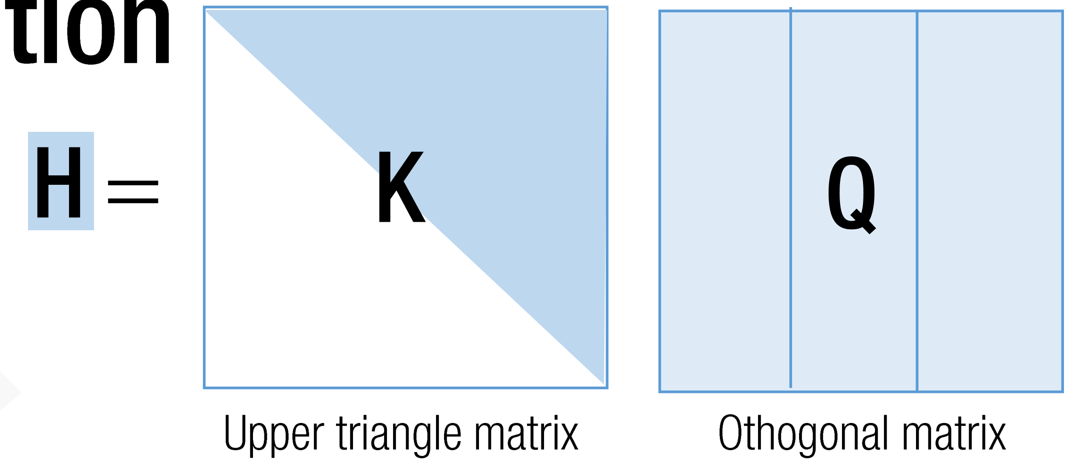


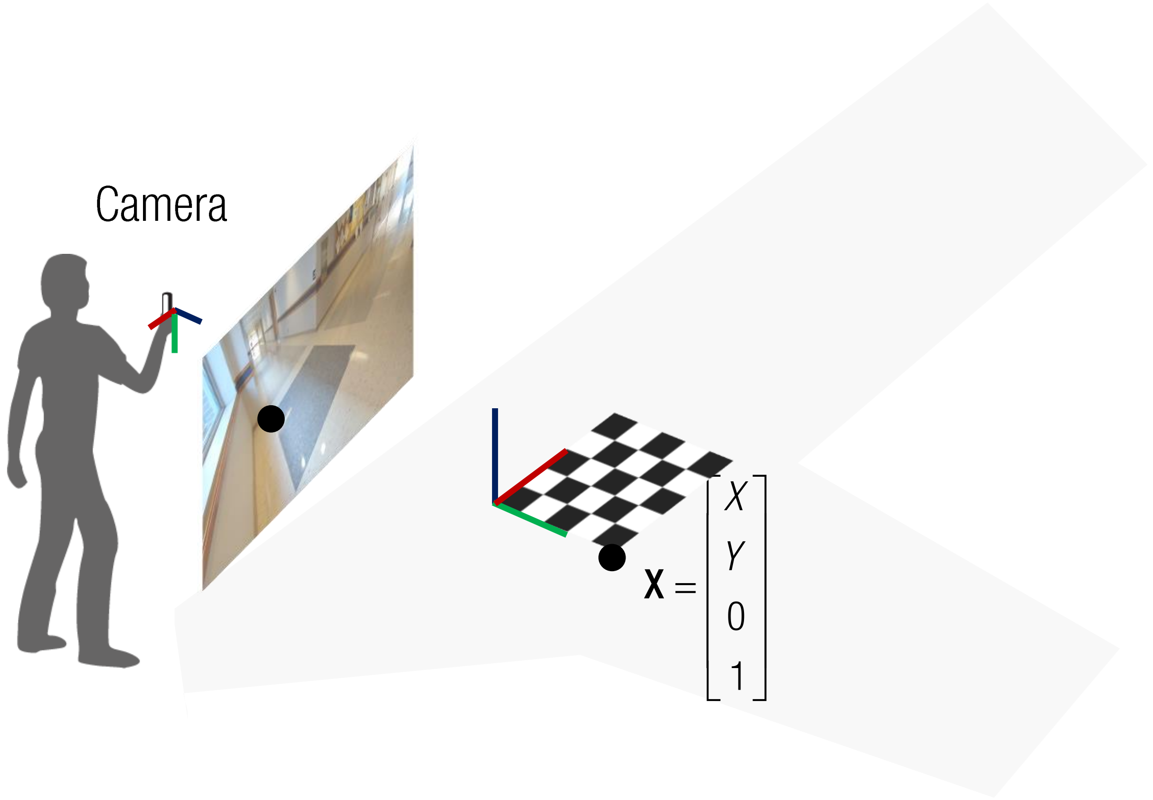
Method1: RQ Decomposition



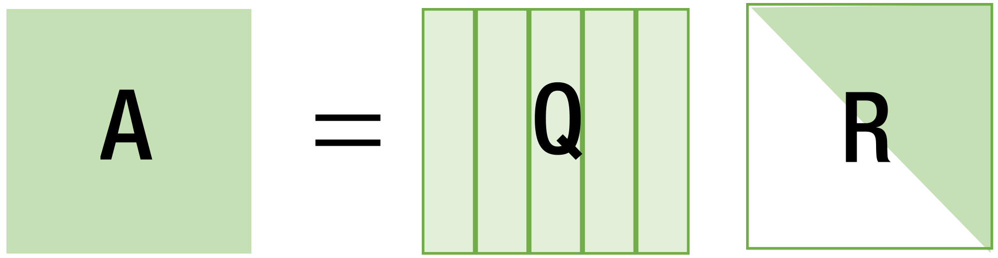


Method1: RQ Decomposition

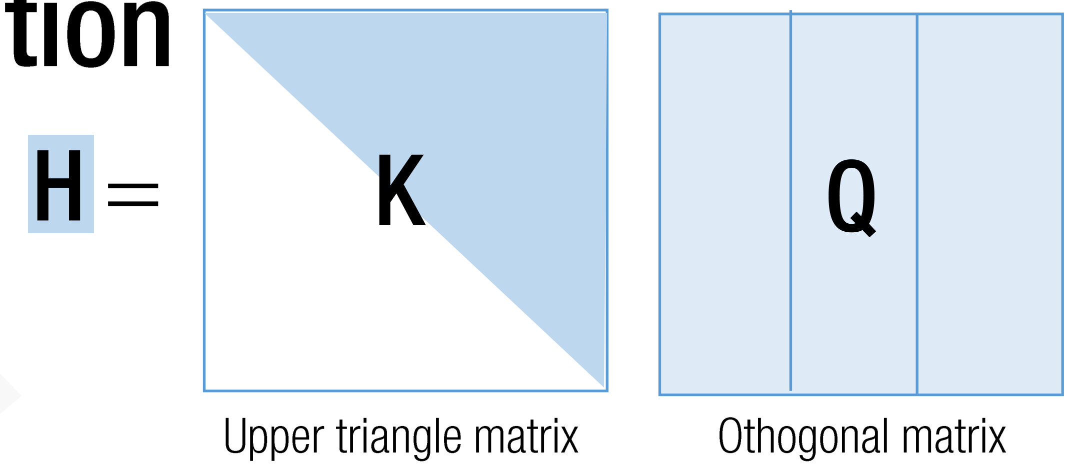


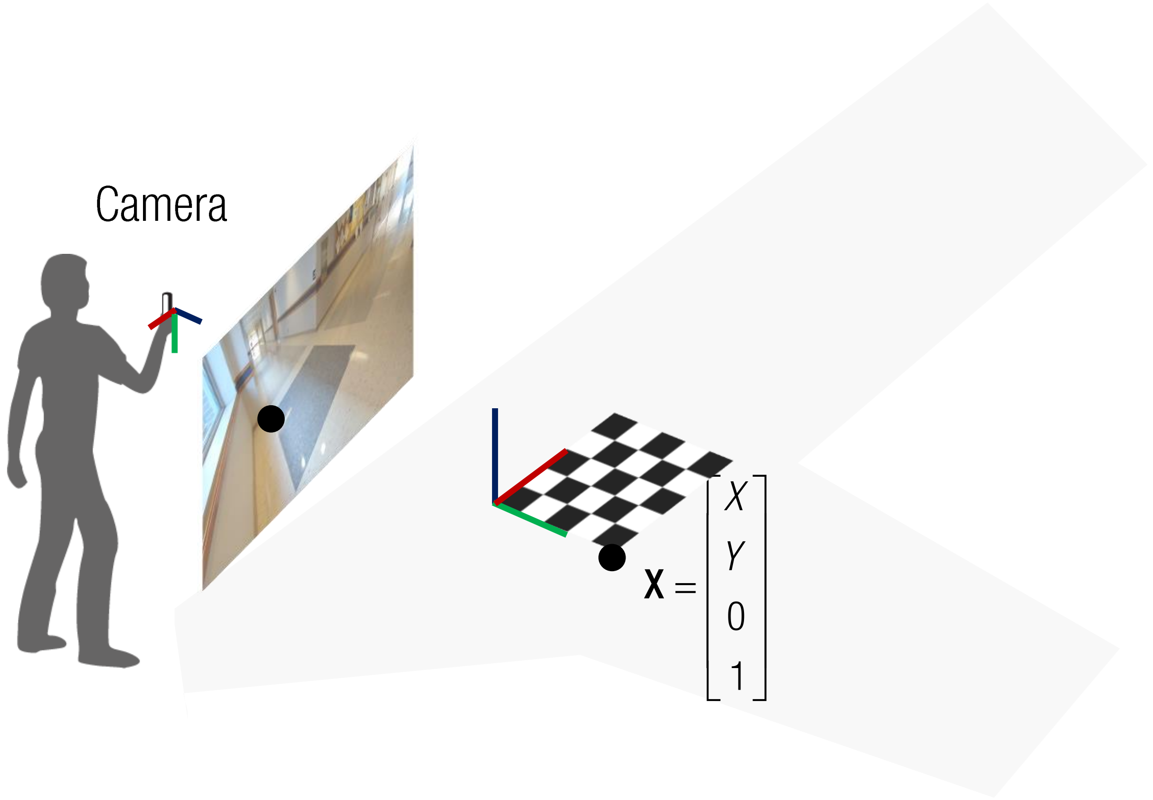


QR decomposition:



Method1: RQ Decomposition





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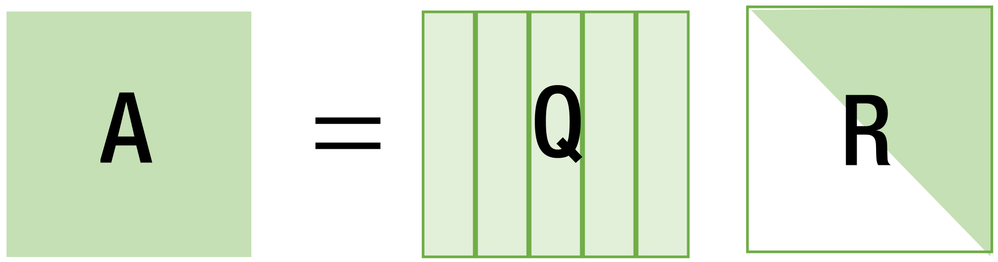
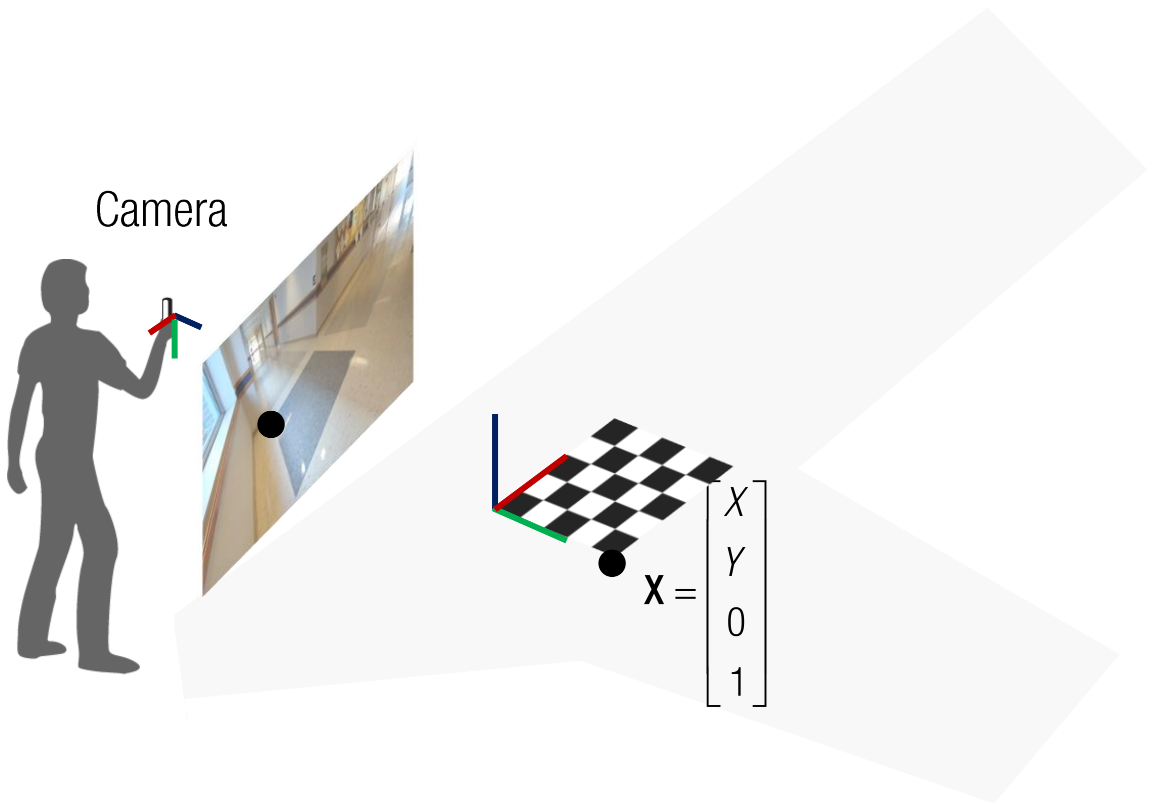
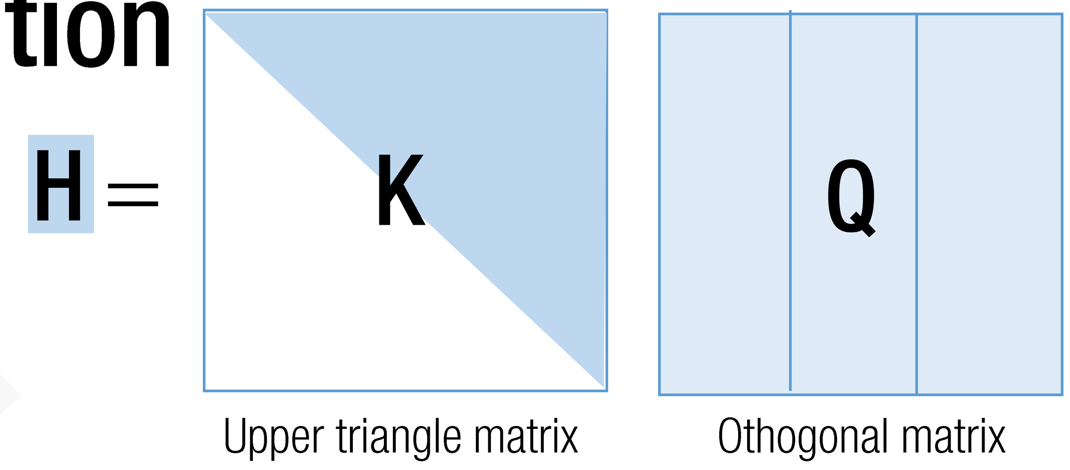


MATLAB

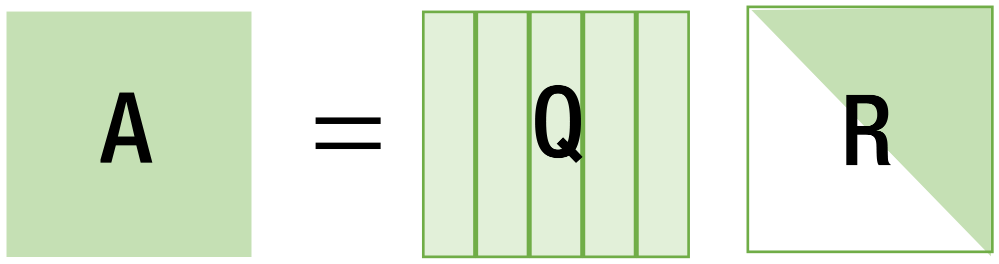
[Q R] = qr(A)

Method1: RQ Decomposition





QR decomposition:

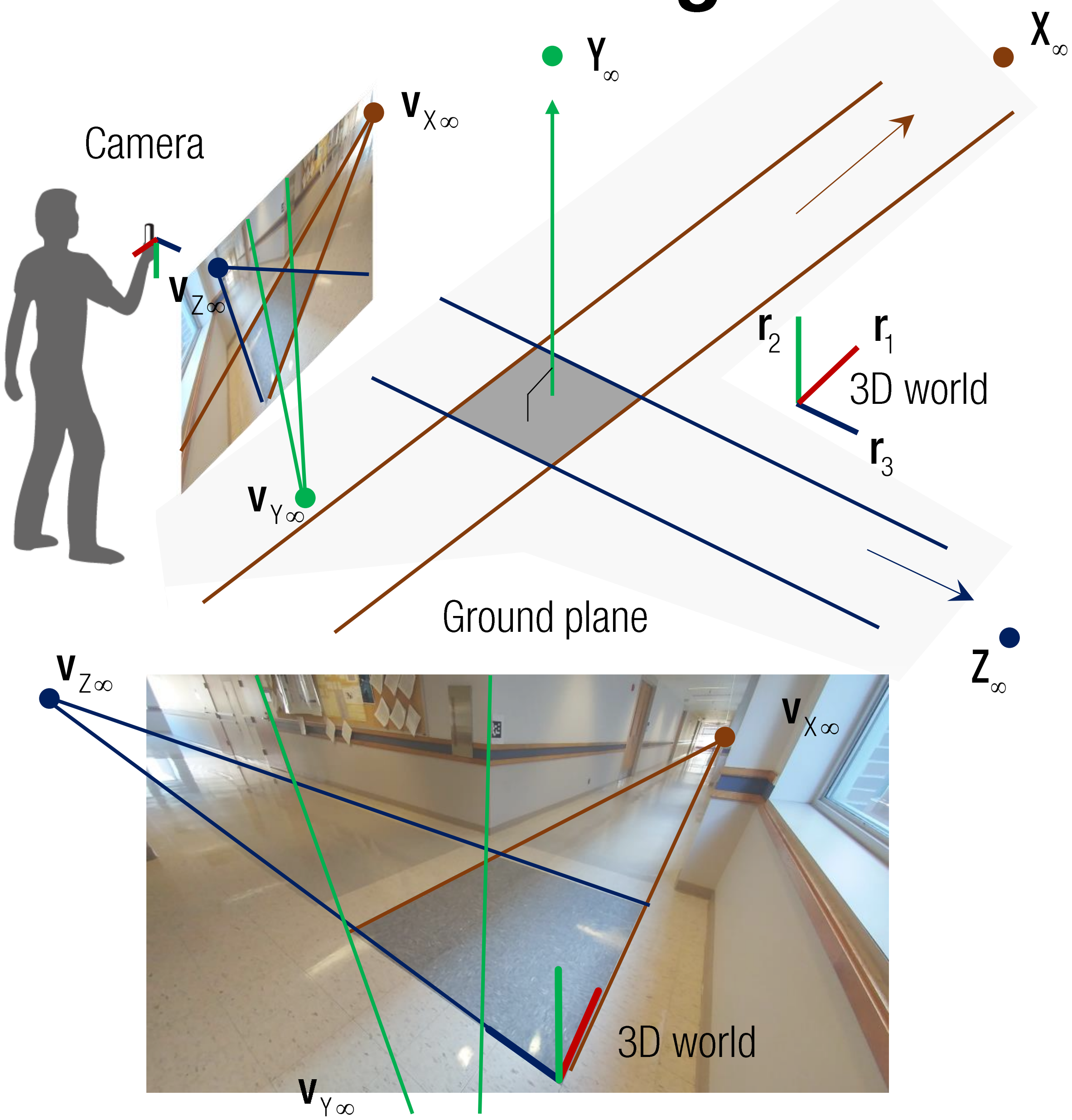


MATLAB

[Q R] = qr(A)

How to convert **QR** to **RQ**?

Recall: Vanishing Points



$$\lambda \mathbf{v}_{X\infty} = \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix} \mathbf{R}\mathbf{X}_\infty \quad \lambda \mathbf{v}_{Z\infty} = \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix} \mathbf{R}\mathbf{Z}_\infty \quad \lambda \mathbf{v}_{Y\infty} = \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix} \mathbf{R}\mathbf{Y}_\infty$$

$$\lambda \mathbf{K}^{-1}\mathbf{v}_{X\infty} = \mathbf{R}\mathbf{X}_\infty \qquad \lambda \mathbf{K}^{-1}\mathbf{v}_{Y\infty} = \mathbf{R}\mathbf{Y}_\infty \qquad \lambda \mathbf{K}^{-1}\mathbf{v}_{Z\infty} = \mathbf{R}\mathbf{Z}_\infty$$

Note that the camera extrinsic is still unknown (**R** and **t**).

Known property of points at infinity:

$$(\mathbf{X}_\infty)^\mathsf{T}(\mathbf{Y}_\infty) = 0 \qquad (\mathbf{R}\mathbf{X}_\infty)^\mathsf{T}(\mathbf{R}\mathbf{Y}_\infty) = 0$$

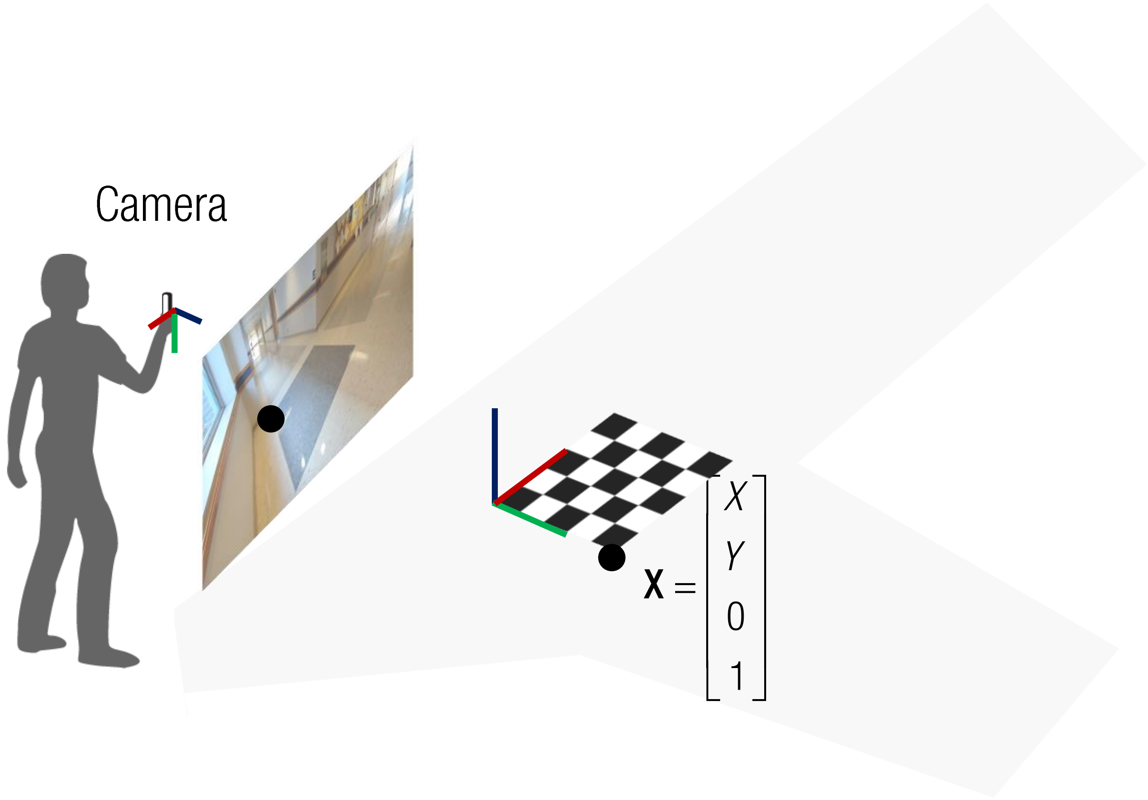
$$(\mathbf{Y}_\infty)^\mathsf{T}(\mathbf{Z}_\infty) = 0 \quad \longleftrightarrow \quad (\mathbf{R}\mathbf{Y}_\infty)^\mathsf{T}(\mathbf{R}\mathbf{Z}_\infty) = 0$$

$$(\mathbf{Z}_\infty)^\mathsf{T}(\mathbf{X}_\infty) = 0 \qquad (\mathbf{R}\mathbf{Z}_\infty)^\mathsf{T}(\mathbf{R}\mathbf{X}_\infty) = 0$$

$$(\mathbf{K}^{-1}\mathbf{v}_{X\infty})^\mathsf{T}(\mathbf{K}^{-1}\mathbf{v}_{Y\infty}) = (\mathbf{K}^{-1}\mathbf{v}_{Y\infty})^\mathsf{T}(\mathbf{K}^{-1}\mathbf{v}_{Z\infty}) = (\mathbf{K}^{-1}\mathbf{v}_{Z\infty})^\mathsf{T}(\mathbf{K}^{-1}\mathbf{v}_{X\infty}) = 0$$

: 3 unknowns and 3 equations

Method2: Rotation



$$\mathbf{X} = \begin{bmatrix} X \\ Y \\ 0 \\ 1 \end{bmatrix}$$

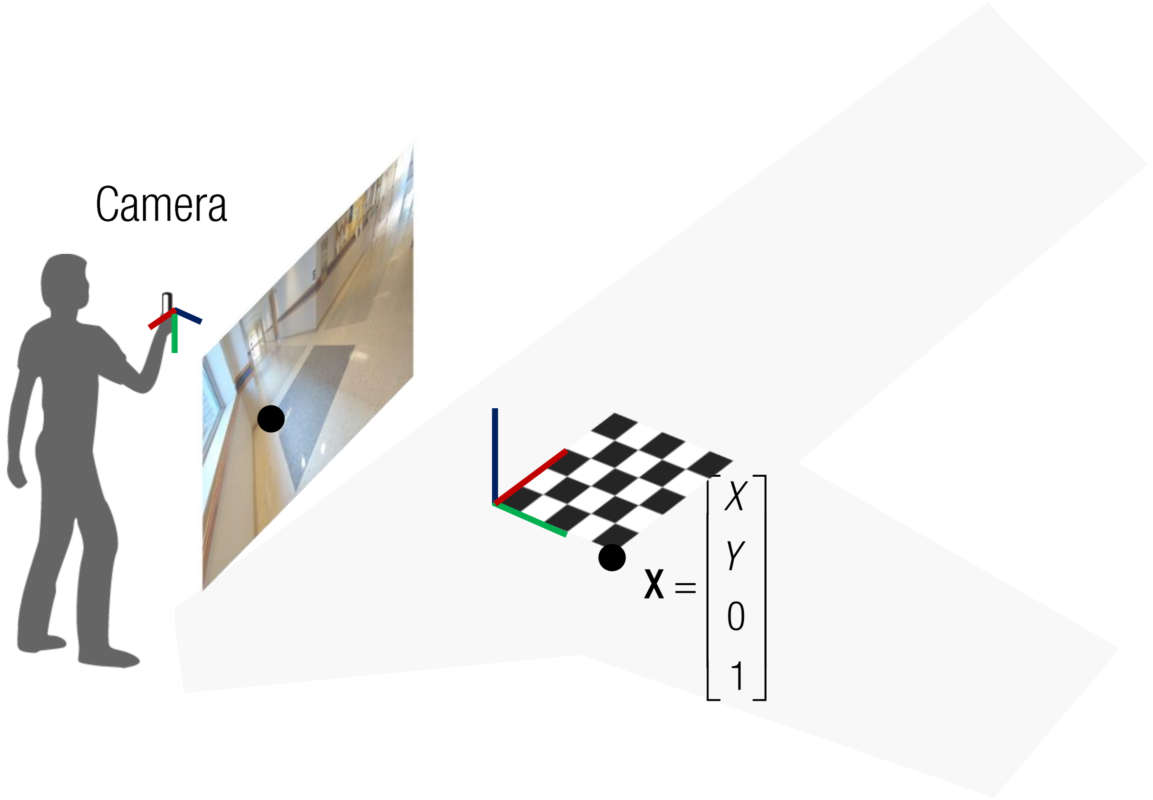
: Knowns

: Unknowns

Homography factorization:

$$\begin{bmatrix} \mathbf{h}_1 & \mathbf{h}_2 & \mathbf{h}_3 \end{bmatrix} = \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix} \begin{bmatrix} \mathbf{r}_1 & \mathbf{r}_2 & \mathbf{t} \end{bmatrix}$$

Method2: Rotation



$$\mathbf{X} = \begin{bmatrix} X \\ Y \\ 0 \\ 1 \end{bmatrix}$$

: Knowns

: Unknowns

Homography factorization:

$$\left(\begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix} \right)^{-1} \begin{bmatrix} \mathbf{h}_1 & \mathbf{h}_2 & \mathbf{h}_3 \end{bmatrix} = \begin{bmatrix} \mathbf{r}_1 & \mathbf{r}_2 & \mathbf{t} \end{bmatrix}$$

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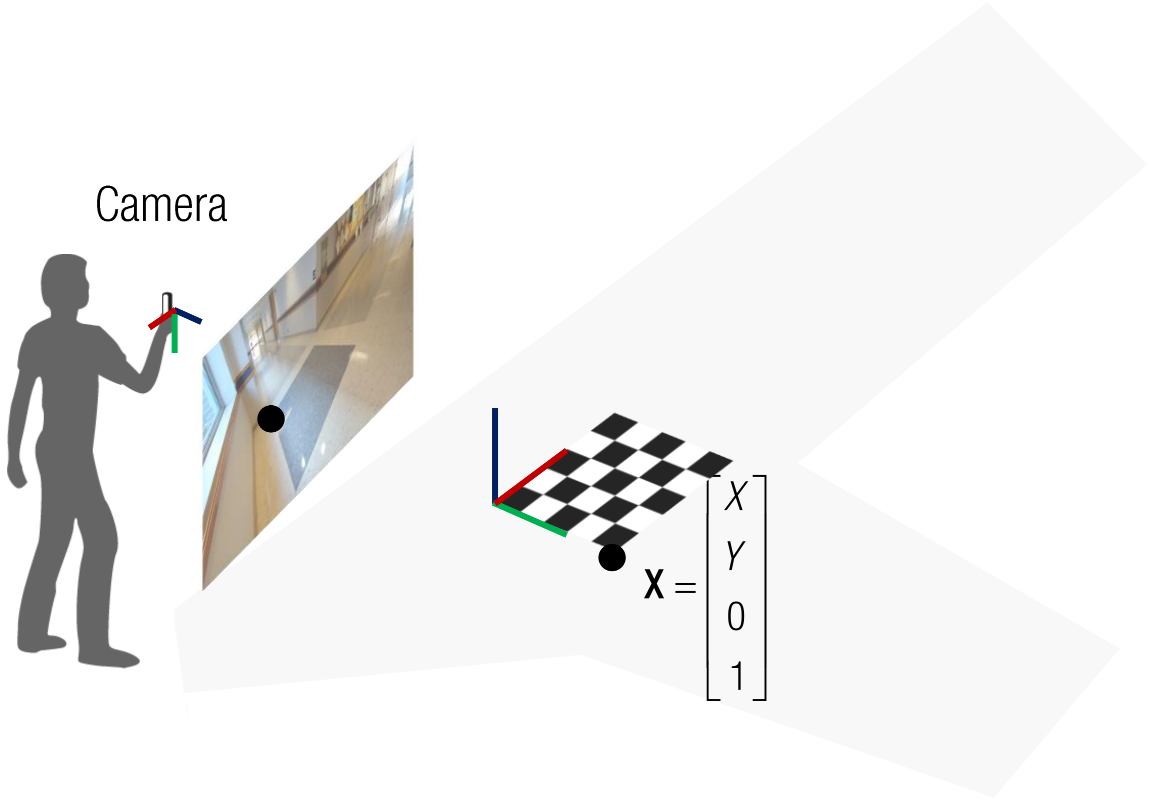


Homography factorization:

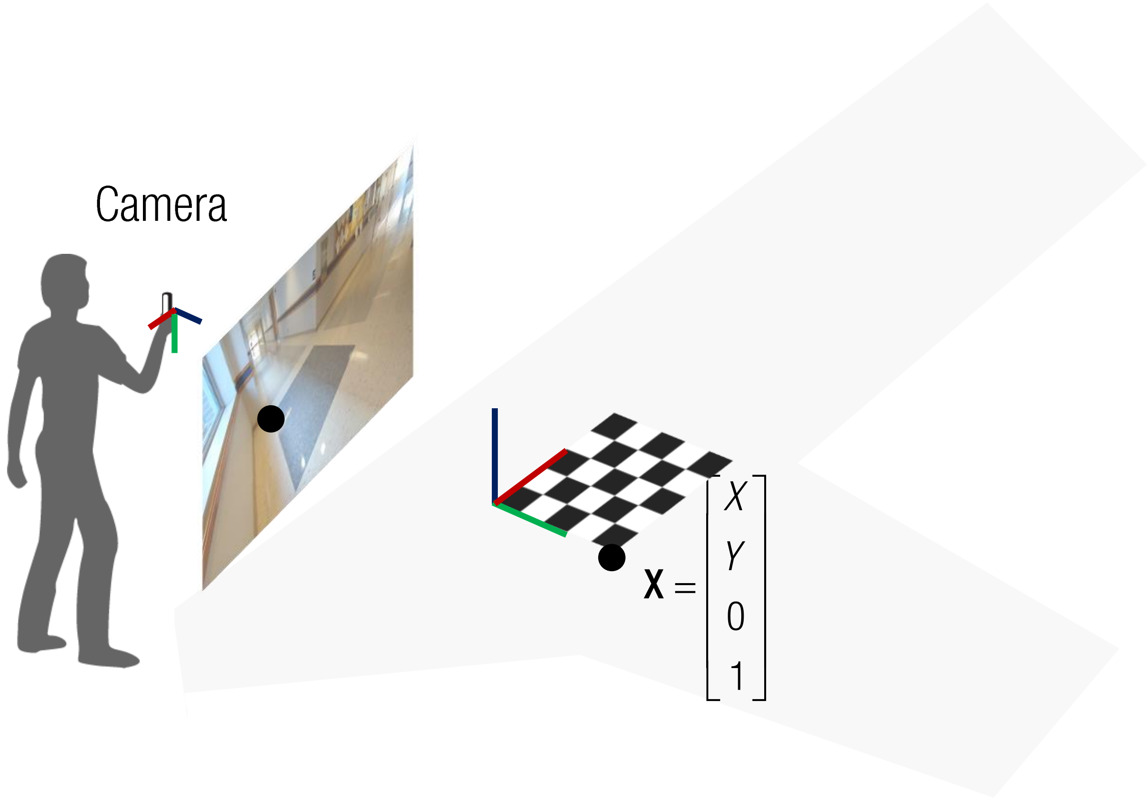
: Knowns

: Unknowns

$$\left(\begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix}\right)^{-1} \begin{bmatrix} \mathbf{h}_1 & \mathbf{h}_2 & \mathbf{h}_3 \end{bmatrix} = \begin{bmatrix} \mathbf{r}_1 & \mathbf{r}_2 & \mathbf{t} \end{bmatrix}$$

$$\mathbf{r}_1 = \mathbf{K}^{-1}\mathbf{h}_1 \qquad \mathbf{r}_2 = \mathbf{K}^{-1}\mathbf{h}_2 \qquad \mathbf{t} = \mathbf{K}^{-1}\mathbf{h}_3$$

Method2: Rotation



$$\mathbf{r}_1 = \mathbf{K}^{-1}\mathbf{h}_1 \qquad \mathbf{r}_2 = \mathbf{K}^{-1}\mathbf{h}_2 \qquad \mathbf{t} = \mathbf{K}^{-1}\mathbf{h}_3$$

Orthogonality of rotation matrix property:

$$\mathbf{r}_1^{\mathsf{T}}\mathbf{r}_2 = 0 \qquad \left\|\mathbf{r}_1\right\| = 1 \qquad \left\|\mathbf{r}_2\right\| = 1$$

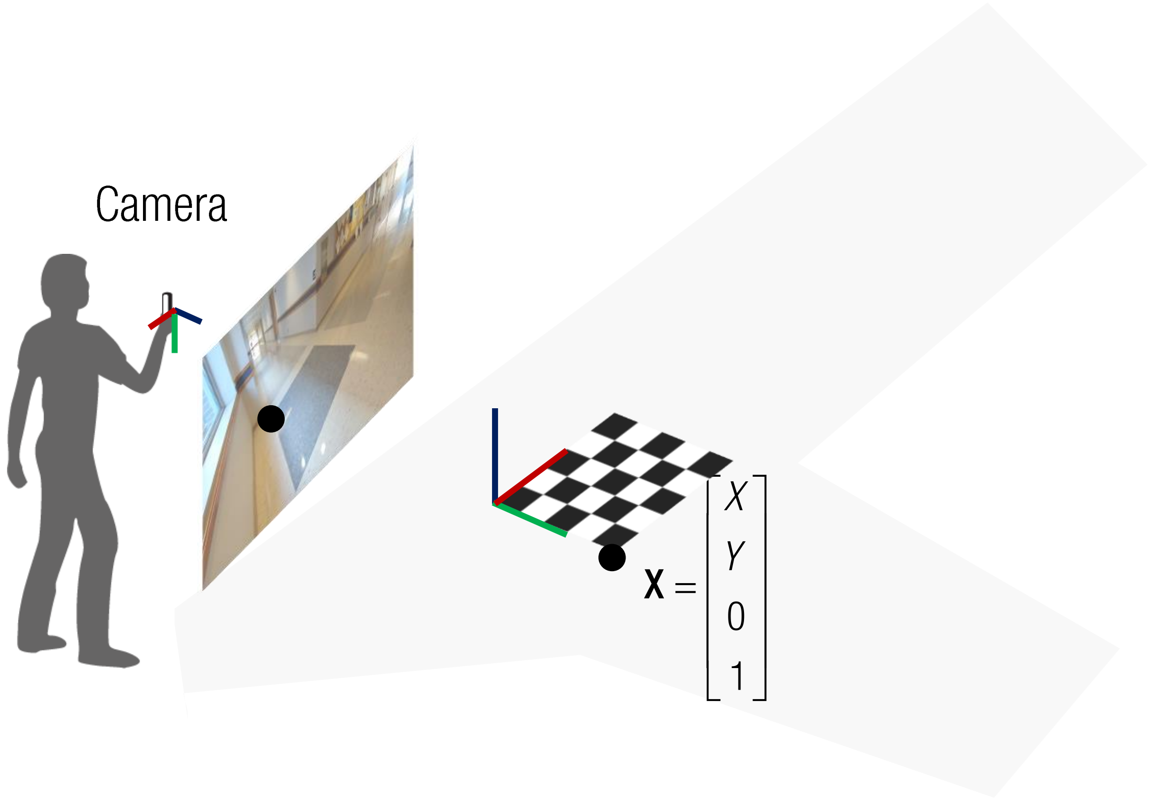
Method2: Rotation

$$\mathbf{r}_1 = \mathbf{K}^{-1}\mathbf{h}_1 \qquad \mathbf{r}_2 = \mathbf{K}^{-1}\mathbf{h}_2 \qquad \mathbf{t} = \mathbf{K}^{-1}\mathbf{h}_3$$

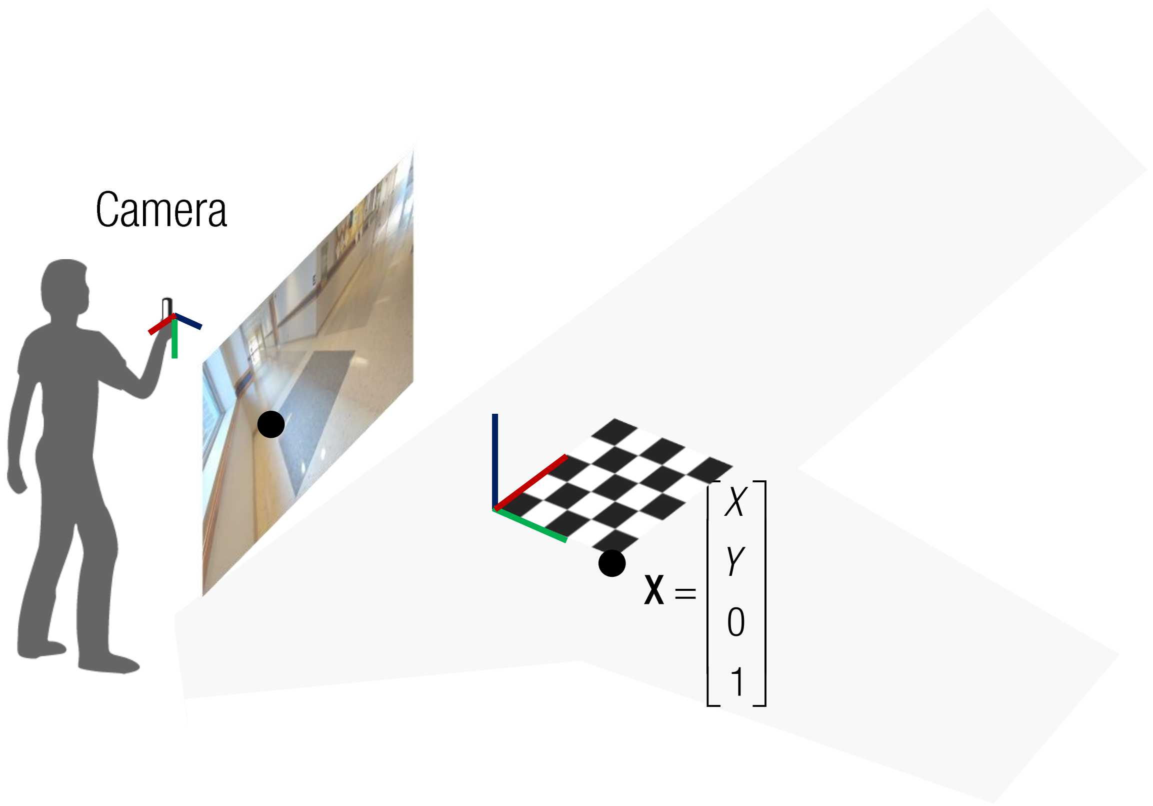
Orthogonality of rotation matrix property:

$$\mathbf{r}_1^{\mathsf{T}}\mathbf{r}_2 = 0 \qquad \|\mathbf{r}_1\| = 1 \qquad \|\mathbf{r}_2\| = 1$$

$$\longrightarrow \left(\mathbf{K}^{-1}\mathbf{h}_1\right)^{\mathsf{T}}\left(\mathbf{K}^{-1}\mathbf{h}_2\right) = \mathbf{h}_1^{\mathsf{T}}\mathbf{K}^{-\mathsf{T}}\mathbf{K}^{-1}\mathbf{h}_2 = 0$$



Method2: Rotation



$$\mathbf{r}_1 = \mathbf{K}^{-1}\mathbf{h}_1 \qquad \mathbf{r}_2 = \mathbf{K}^{-1}\mathbf{h}_2 \qquad \mathbf{t} = \mathbf{K}^{-1}\mathbf{h}_3$$

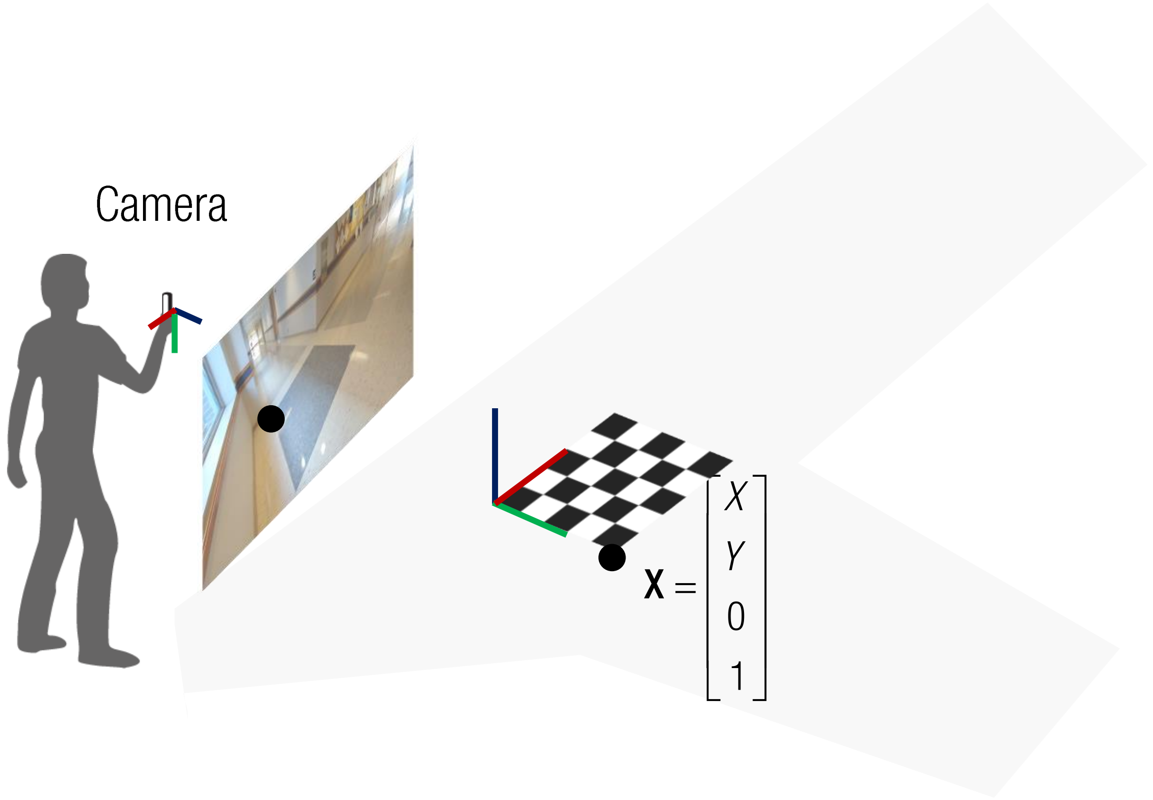
Orthogonality of rotation matrix property:

$$\mathbf{r}_1^{\mathsf{T}}\mathbf{r}_2 = 0 \qquad \left\|\mathbf{r}_1\right\| = 1 \qquad \left\|\mathbf{r}_2\right\| = 1$$

$$\longrightarrow \left(\mathbf{K}^{-1}\mathbf{h}_1\right)^{\mathsf{T}}\left(\mathbf{K}^{-1}\mathbf{h}_2\right) = \mathbf{h}_1^{\mathsf{T}}\mathbf{K}^{-\mathsf{T}}\mathbf{K}^{-1}\mathbf{h}_2 = 0$$

$$\left\|\mathbf{K}^{-1}\mathbf{h}_1\right\| = \left\|\mathbf{K}^{-1}\mathbf{h}_2\right\| \quad \text{or,} \quad \mathbf{h}_1^{\mathsf{T}}\mathbf{K}^{-\mathsf{T}}\mathbf{K}^{-1}\mathbf{h}_1 = \mathbf{h}_2^{\mathsf{T}}\mathbf{K}^{-\mathsf{T}}\mathbf{K}^{-1}\mathbf{h}_2$$

Method2: Rotation



$$\mathbf{r}_1 = \mathbf{K}^{-1}\mathbf{h}_1 \qquad \mathbf{r}_2 = \mathbf{K}^{-1}\mathbf{h}_2 \qquad \mathbf{t} = \mathbf{K}^{-1}\mathbf{h}_3$$

Orthogonality of rotation matrix property:

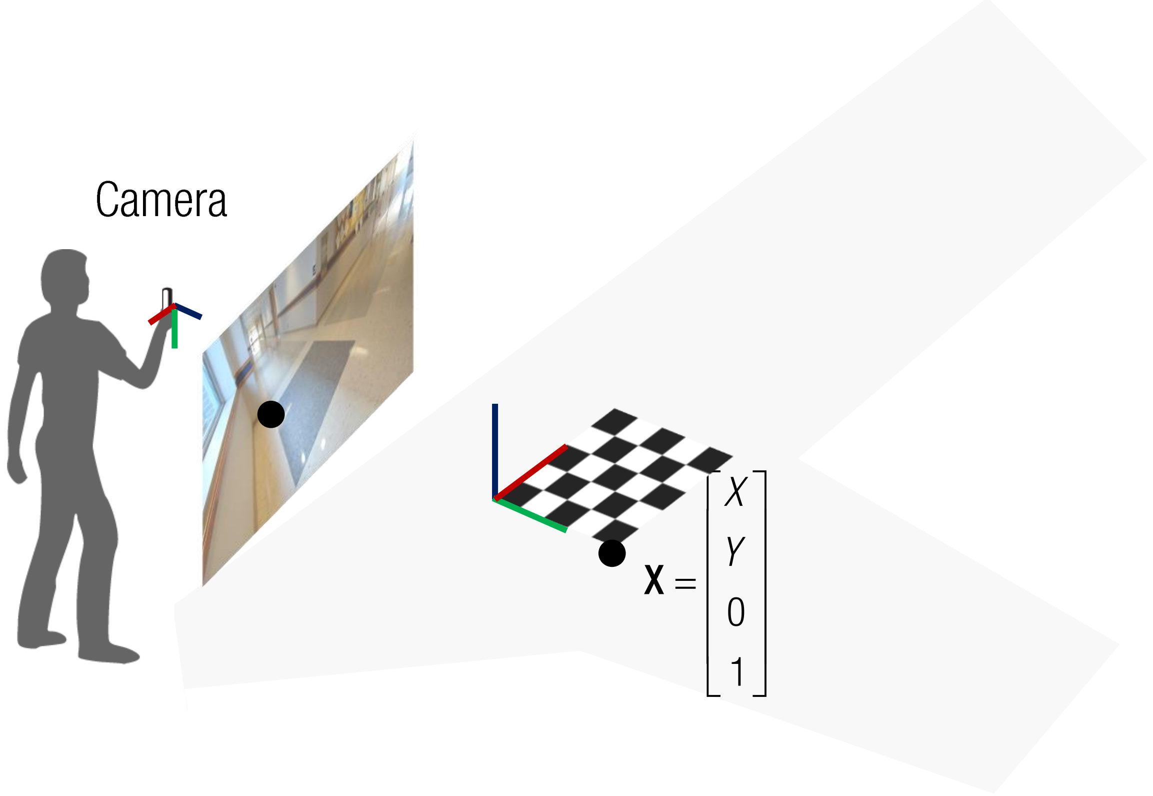
$$\mathbf{r}_1^T\mathbf{r}_2 = 0 \qquad \|\mathbf{r}_1\| = 1 \qquad \|\mathbf{r}_2\| = 1$$

$$\longrightarrow \left(\mathbf{K}^{-1}\mathbf{h}_1\right)^T\left(\mathbf{K}^{-1}\mathbf{h}_2\right) = \mathbf{h}_1^T\mathbf{K}^{-T}\mathbf{K}^{-1}\mathbf{h}_2 = 0$$

$$\|\mathbf{K}^{-1}\mathbf{h}_1\| = \|\mathbf{K}^{-1}\mathbf{h}_2\| \quad \text{or,} \quad \mathbf{h}_1^T\mathbf{K}^{-T}\mathbf{K}^{-1}\mathbf{h}_1 = \mathbf{h}_2^T\mathbf{K}^{-T}\mathbf{K}^{-1}\mathbf{h}_2$$

$$\mathbf{K}^{-T}\mathbf{K}^{-1} =$$

Method2: Rotation



$$\mathbf{r}_1 = \mathbf{K}^{-1}\mathbf{h}_1 \qquad \mathbf{r}_2 = \mathbf{K}^{-1}\mathbf{h}_2 \qquad \mathbf{t} = \mathbf{K}^{-1}\mathbf{h}_3$$

Orthogonality of rotation matrix property:

$$\mathbf{r}_1^{\mathsf{T}}\mathbf{r}_2 = 0 \qquad \left\|\mathbf{r}_1\right\| = 1 \qquad \left\|\mathbf{r}_2\right\| = 1$$

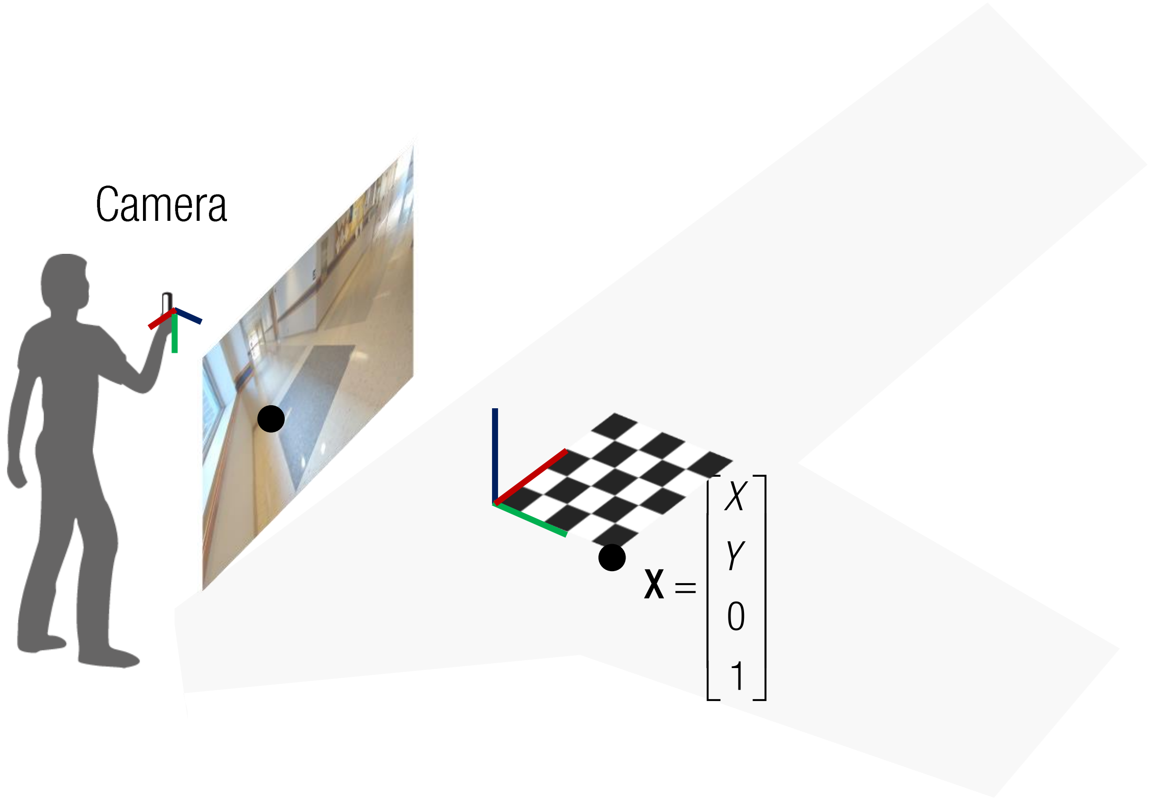
$$\longrightarrow \left(\mathbf{K}^{-1}\mathbf{h}_1\right)^{\mathsf{T}}\left(\mathbf{K}^{-1}\mathbf{h}_2\right) = \mathbf{h}_1^{\mathsf{T}}\mathbf{K}^{-\mathsf{T}}\mathbf{K}^{-1}\mathbf{h}_2 = 0$$

$$\left\|\mathbf{K}^{-1}\mathbf{h}_1\right\| = \left\|\mathbf{K}^{-1}\mathbf{h}_2\right\| \quad \text{or,} \quad \mathbf{h}_1^{\mathsf{T}}\mathbf{K}^{-\mathsf{T}}\mathbf{K}^{-1}\mathbf{h}_1 = \mathbf{h}_2^{\mathsf{T}}\mathbf{K}^{-\mathsf{T}}\mathbf{K}^{-1}\mathbf{h}_2$$

$$\mathbf{K}^{-\mathsf{T}}\mathbf{K}^{-1} = \begin{bmatrix} 1/f & & \\ & 1/f & \\ -p_x/f & -p_y/f & 1 \end{bmatrix}\begin{bmatrix} 1/f & & -p_x/f \\ & 1/f & -p_y/f \\ & & 1 \end{bmatrix}$$

$$\mathbf{X} = \begin{bmatrix} X \\ Y \\ 0 \\ 1 \end{bmatrix}$$

Method2: Rotation



$$\mathbf{r}_1 = \mathbf{K}^{-1}\mathbf{h}_1 \qquad \mathbf{r}_2 = \mathbf{K}^{-1}\mathbf{h}_2 \qquad \mathbf{t} = \mathbf{K}^{-1}\mathbf{h}_3$$

Orthogonality of rotation matrix property:

$$\mathbf{r}_1^{\mathsf{T}}\mathbf{r}_2 = 0 \qquad \|\mathbf{r}_1\| = 1 \qquad \|\mathbf{r}_2\| = 1$$

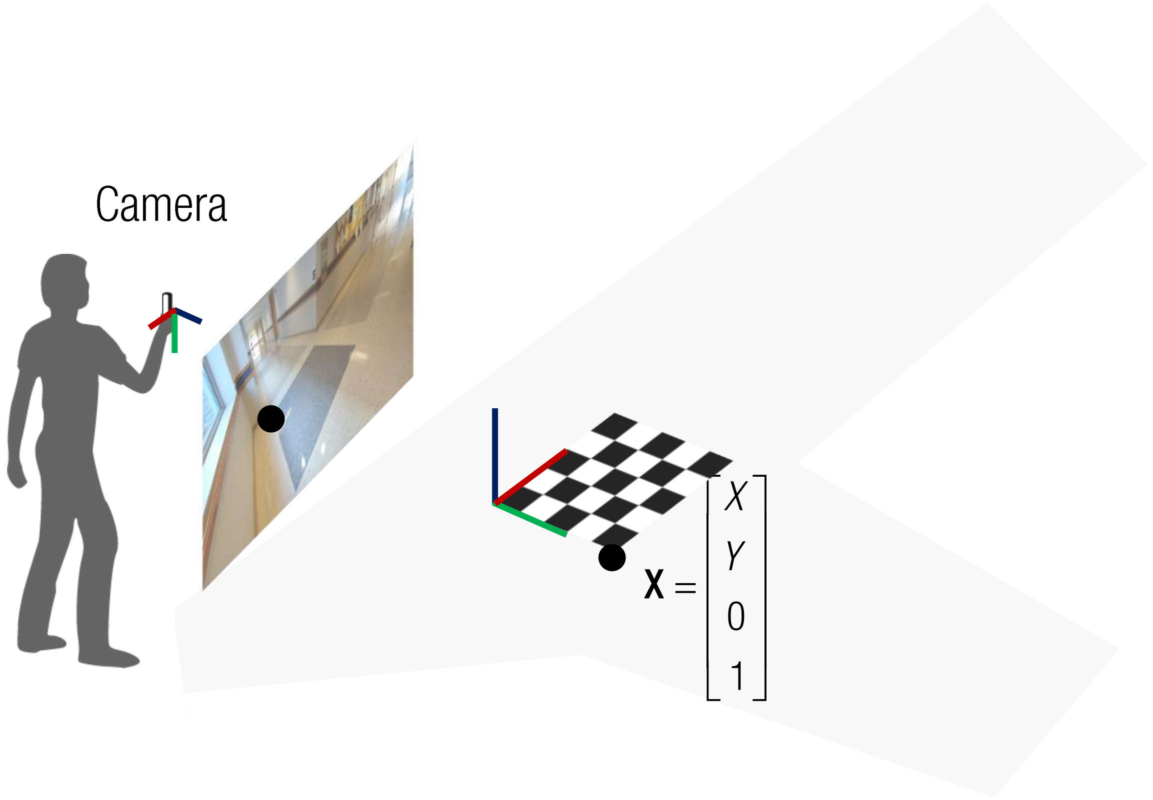
$$\longrightarrow \left(\mathbf{K}^{-1}\mathbf{h}_1\right)^{\mathsf{T}}\left(\mathbf{K}^{-1}\mathbf{h}_2\right) = \mathbf{h}_1^{\mathsf{T}}\mathbf{K}^{-\mathsf{T}}\mathbf{K}^{-1}\mathbf{h}_2 = 0$$

$$\|\mathbf{K}^{-1}\mathbf{h}_1\| = \|\mathbf{K}^{-1}\mathbf{h}_2\| \quad \text{or,} \quad \mathbf{h}_1^{\mathsf{T}}\mathbf{K}^{-\mathsf{T}}\mathbf{K}^{-1}\mathbf{h}_1 = \mathbf{h}_2^{\mathsf{T}}\mathbf{K}^{-\mathsf{T}}\mathbf{K}^{-1}\mathbf{h}_2$$

$$\mathbf{K}^{-\mathsf{T}}\mathbf{K}^{-1} = \begin{bmatrix} 1/f & & \\ & 1/f & \\ -p_x/f & -p_y/f & 1 \end{bmatrix}\begin{bmatrix} 1/f & & -p_x/f \\ & 1/f & -p_y/f \\ & & 1 \end{bmatrix} = \begin{bmatrix} b_1 & & b_2 \\ & b_1 & b_3 \\ b_2 & b_3 & b_4 \end{bmatrix}$$

where $b_1 = \frac{1}{f^2}, \quad b_2 = -\frac{p_x}{f^2}, \quad b_3 = -\frac{p_y}{f^2}, \quad b_4 = \frac{p_x^2}{f^2} + \frac{p_y^2}{f^2} + 1$

Method2: Rotation



$$\mathbf{X} = \begin{bmatrix} X \\ Y \\ 0 \\ 1 \end{bmatrix}$$

$$\mathbf{r}_1 = \mathbf{K}^{-1}\mathbf{h}_1 \qquad \mathbf{r}_2 = \mathbf{K}^{-1}\mathbf{h}_2 \qquad \mathbf{t} = \mathbf{K}^{-1}\mathbf{h}_3$$

Orthogonality of rotation matrix property:

$$\mathbf{r}_1^{\mathsf{T}}\mathbf{r}_2 = 0 \qquad \left\|\mathbf{r}_1\right\| = 1 \qquad \left\|\mathbf{r}_2\right\| = 1$$

$$\longrightarrow \left(\mathbf{K}^{-1}\mathbf{h}_1\right)^{\mathsf{T}}\left(\mathbf{K}^{-1}\mathbf{h}_2\right) = \mathbf{h}_1^{\mathsf{T}}\mathbf{K}^{-\mathsf{T}}\mathbf{K}^{-1}\mathbf{h}_2 = 0$$

$$\left\|\mathbf{K}^{-1}\mathbf{h}_1\right\| = \left\|\mathbf{K}^{-1}\mathbf{h}_2\right\| \quad \text{or,} \quad \mathbf{h}_1^{\mathsf{T}}\mathbf{K}^{-\mathsf{T}}\mathbf{K}^{-1}\mathbf{h}_1 = \mathbf{h}_2^{\mathsf{T}}\mathbf{K}^{-\mathsf{T}}\mathbf{K}^{-1}\mathbf{h}_2$$

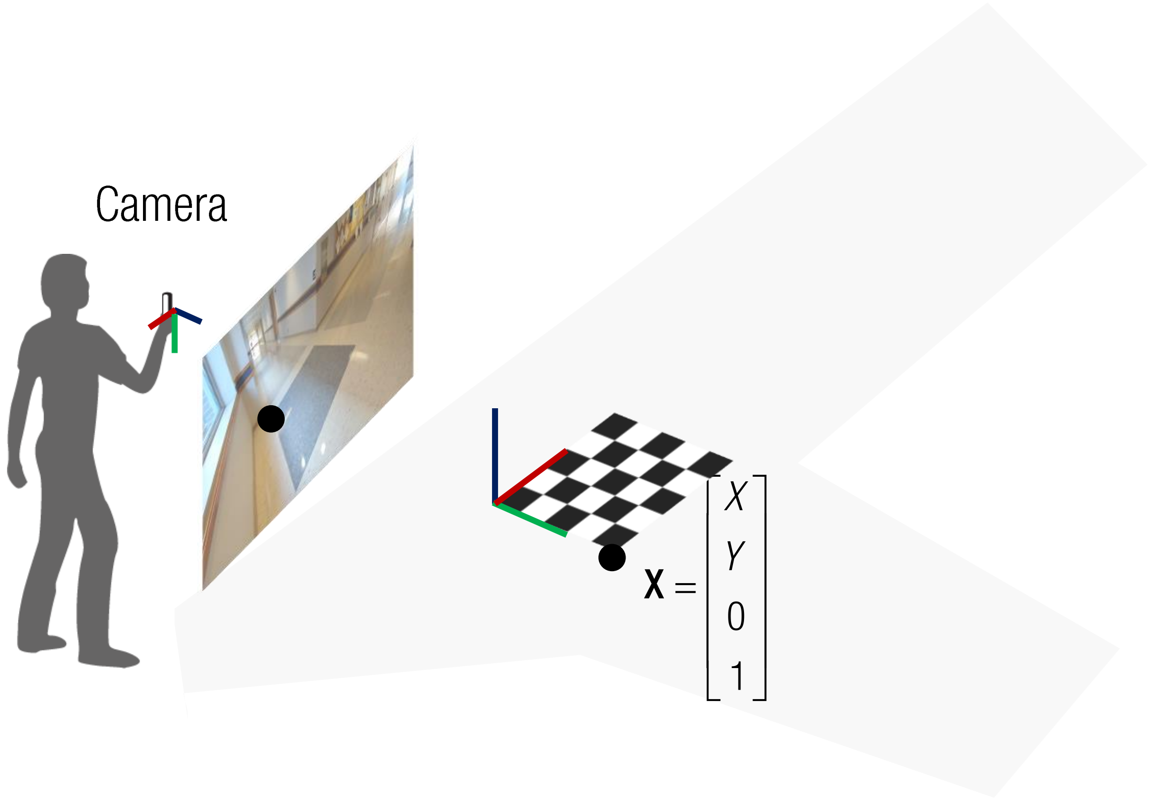
$$\mathbf{K}^{-\mathsf{T}}\mathbf{K}^{-1} = \begin{bmatrix} 1/f & & \\ & 1/f & \\ -p_x/f & -p_y/f & 1 \end{bmatrix} \begin{bmatrix} 1/f & & -p_x/f \\ & 1/f & -p_y/f \\ & & 1 \end{bmatrix} = \underbrace{\begin{bmatrix} b_1 & & b_2 \\ & b_1 & b_3 \\ b_2 & b_3 & b_4 \end{bmatrix}}_{\mathbf{B}}$$

where $b_1 = \frac{1}{f^2}, \quad b_2 = -\frac{p_x}{f^2}, \quad b_3 = -\frac{p_y}{f^2}, \quad b_4 = \frac{p_x^2}{f^2} + \frac{p_y^2}{f^2} + 1$

Linear in **B**: $\mathbf{h}_1^{\mathsf{T}}\mathbf{B}\mathbf{h}_2 = 0 \qquad \mathbf{h}_1^{\mathsf{T}}\mathbf{B}\mathbf{h}_1 = \mathbf{h}_2^{\mathsf{T}}\mathbf{B}\mathbf{h}_2$

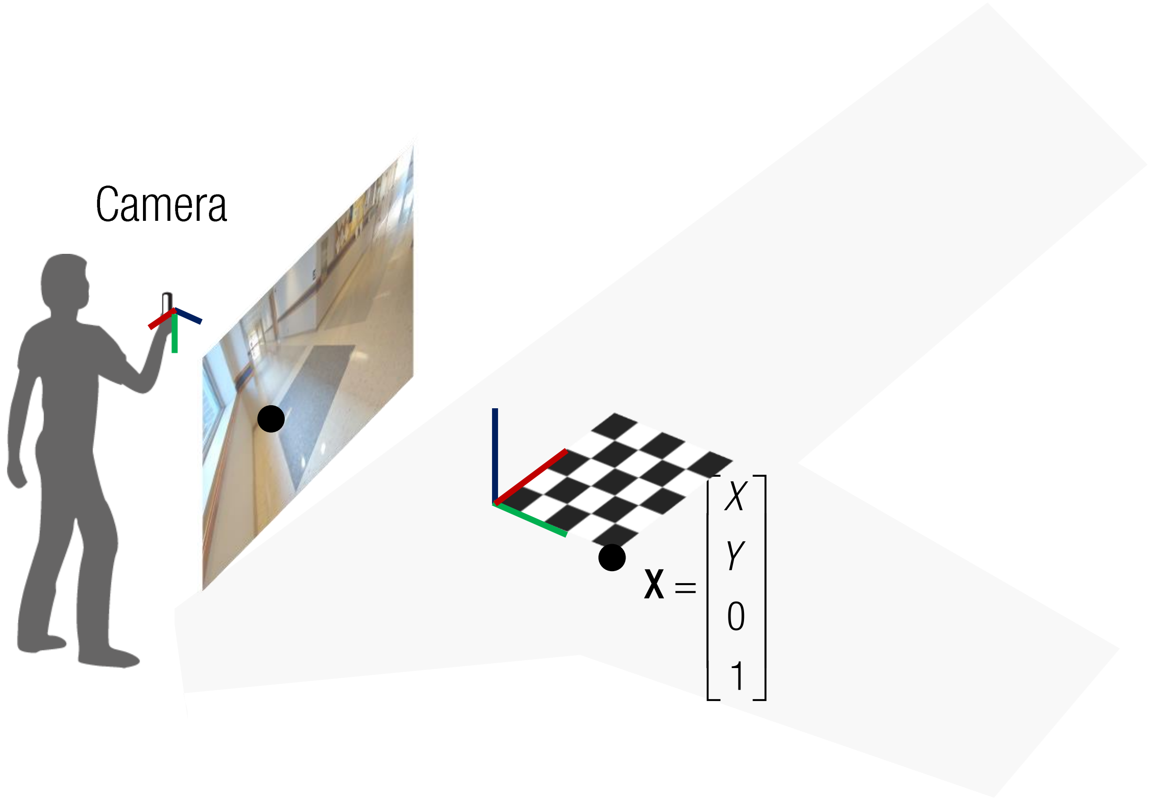
Method2: Rotation

$$\mathbf{h}_1^{\mathsf{T}}\mathbf{B}\mathbf{h}_2 = \begin{bmatrix} h_{11} \\ h_{21} \\ h_{31} \end{bmatrix}^{\mathsf{T}} \begin{bmatrix} b_1 & & b_2 \\ & b_1 & b_3 \\ b_2 & b_3 & b_4 \end{bmatrix} \begin{bmatrix} h_{12} \\ h_{22} \\ h_{32} \end{bmatrix} = 0$$



$$\mathbf{X} = \begin{bmatrix} X \\ Y \\ 0 \\ 1 \end{bmatrix}$$

Method2: Rotation



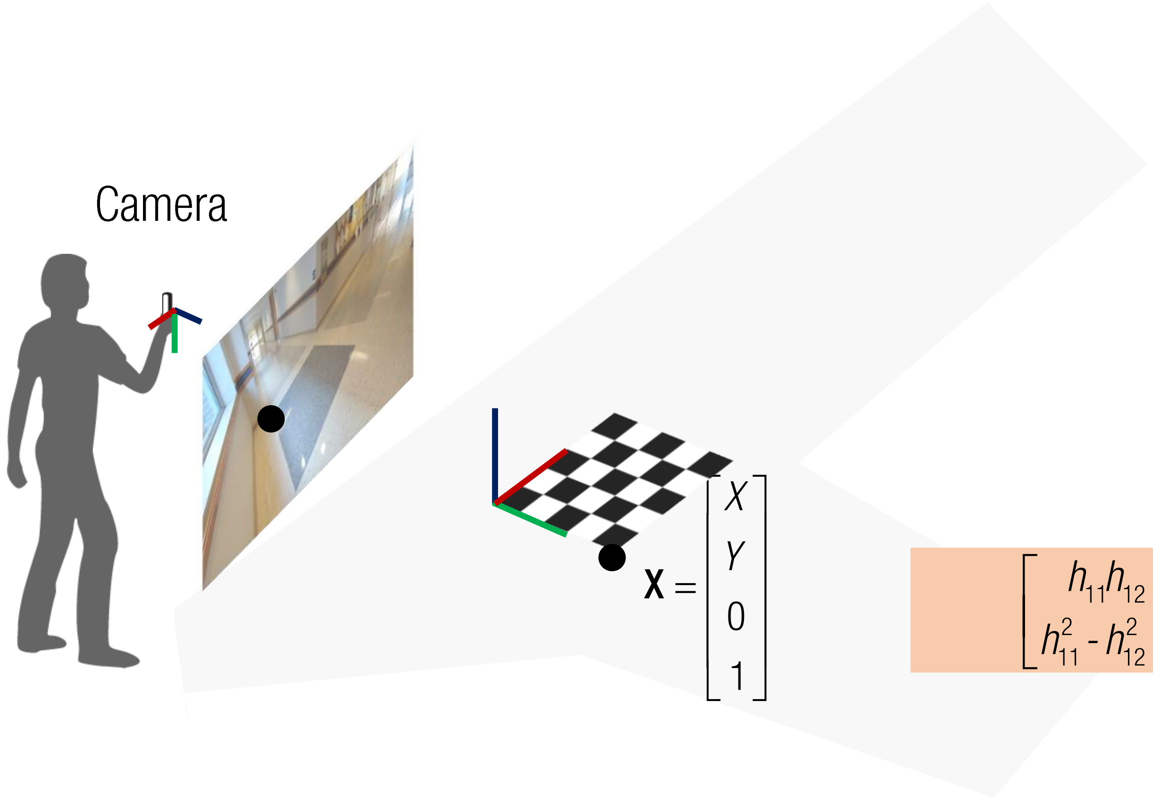
$$\mathbf{X} = \begin{bmatrix} X \\ Y \\ 0 \\ 1 \end{bmatrix}$$

$$\mathbf{h}_1^{\mathsf{T}}\mathbf{B}\mathbf{h}_2 = \begin{bmatrix} h_{11} \\ h_{21} \\ h_{31} \end{bmatrix}^{\mathsf{T}} \begin{bmatrix} b_1 & & b_2 \\ & b_1 & b_3 \\ b_2 & b_3 & b_4 \end{bmatrix} \begin{bmatrix} h_{12} \\ h_{22} \\ h_{32} \end{bmatrix} = 0$$

$$\mathbf{h}_1^{\mathsf{T}}\mathbf{B}\mathbf{h}_1 = \mathbf{h}_2^{\mathsf{T}}\mathbf{B}\mathbf{h}_2$$

$$\begin{bmatrix} h_{11} \\ h_{21} \\ h_{31} \end{bmatrix}^{\mathsf{T}} \begin{bmatrix} b_1 & & b_2 \\ & b_1 & b_3 \\ b_2 & b_3 & b_4 \end{bmatrix} \begin{bmatrix} h_{11} \\ h_{21} \\ h_{31} \end{bmatrix} = \begin{bmatrix} h_{12} \\ h_{22} \\ h_{32} \end{bmatrix}^{\mathsf{T}} \begin{bmatrix} b_1 & & b_2 \\ & b_1 & b_3 \\ b_2 & b_3 & b_4 \end{bmatrix} \begin{bmatrix} h_{12} \\ h_{22} \\ h_{32} \end{bmatrix}$$

Method2: Rotation



$$\mathbf{h}_1^{\mathsf{T}}\mathbf{B}\mathbf{h}_2 = \begin{bmatrix} h_{11} \\ h_{21} \\ h_{31} \end{bmatrix}^{\mathsf{T}} \begin{bmatrix} b_1 & & b_2 \\ & b_1 & b_3 \\ b_2 & b_3 & b_4 \end{bmatrix} \begin{bmatrix} h_{12} \\ h_{22} \\ h_{32} \end{bmatrix} = 0$$

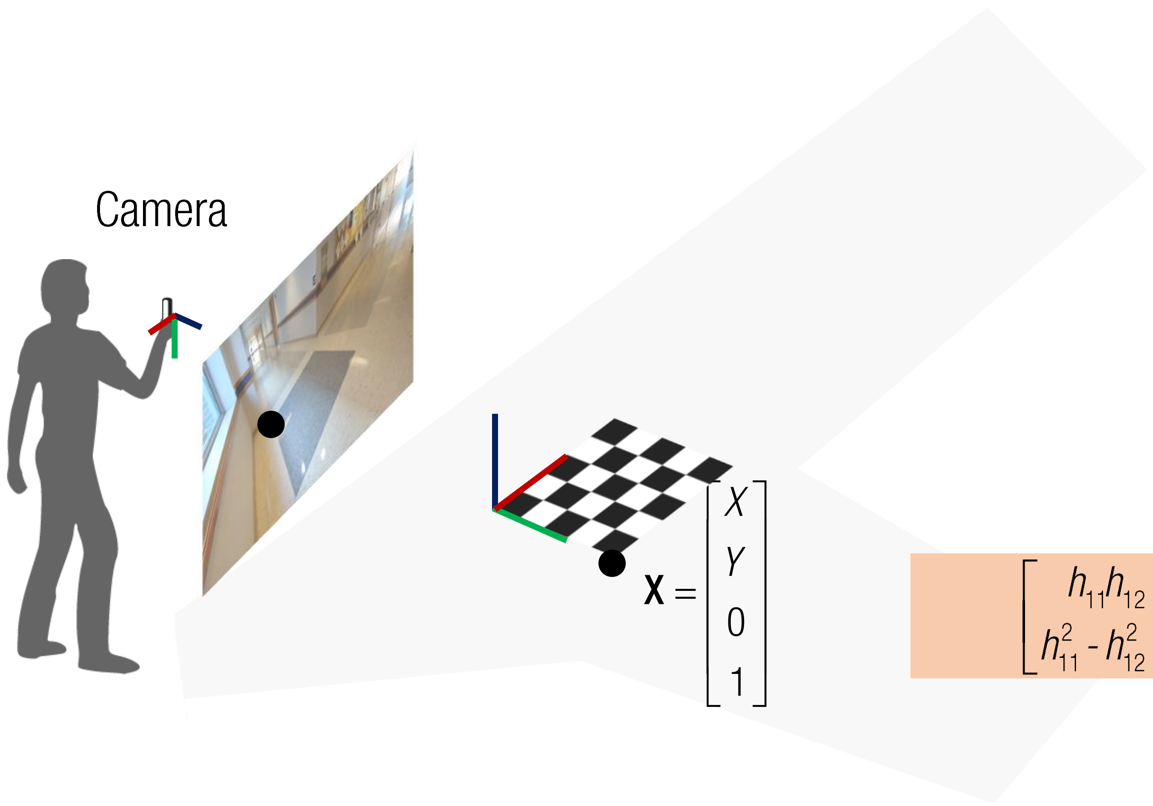
$$\mathbf{h}_1^{\mathsf{T}}\mathbf{B}\mathbf{h}_1 = \mathbf{h}_2^{\mathsf{T}}\mathbf{B}\mathbf{h}_2$$

$$\begin{bmatrix} h_{11} \\ h_{21} \\ h_{31} \end{bmatrix}^{\mathsf{T}} \begin{bmatrix} b_1 & & b_2 \\ & b_1 & b_3 \\ b_2 & b_3 & b_4 \end{bmatrix} \begin{bmatrix} h_{11} \\ h_{21} \\ h_{31} \end{bmatrix} = \begin{bmatrix} h_{12} \\ h_{22} \\ h_{32} \end{bmatrix}^{\mathsf{T}} \begin{bmatrix} b_1 & & b_2 \\ & b_1 & b_3 \\ b_2 & b_3 & b_4 \end{bmatrix} \begin{bmatrix} h_{12} \\ h_{22} \\ h_{32} \end{bmatrix}$$

$$\begin{bmatrix} h_{11}h_{12} + h_{21}h_{22} & h_{11}h_{32} + h_{31}h_{12} & h_{21}h_{32} + h_{31}h_{22} & h_{32}h_{31} \\ h_{11}^2 - h_{12}^2 + h_{21}^2 - h_{22}^2 & 2(h_{11}h_{31} - h_{12}h_{32}) & 2(h_{21}h_{31} - h_{22}h_{32}) & h_{31}^2 - h_{32}^2 \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} = \mathbf{0}$$

2x4

Method2: Rotation



$$\mathbf{X} = \begin{bmatrix} X \\ Y \\ 0 \\ 1 \end{bmatrix}$$

$$\mathbf{h}_1^T \mathbf{B} \mathbf{h}_2 = \begin{bmatrix} h_{11} \\ h_{21} \\ h_{31} \end{bmatrix}^T \begin{bmatrix} b_1 & & b_2 \\ & b_1 & b_3 \\ b_2 & b_3 & b_4 \end{bmatrix} \begin{bmatrix} h_{12} \\ h_{22} \\ h_{32} \end{bmatrix} = 0$$

$$\mathbf{h}_1^T \mathbf{B} \mathbf{h}_1 = \mathbf{h}_2^T \mathbf{B} \mathbf{h}_2$$

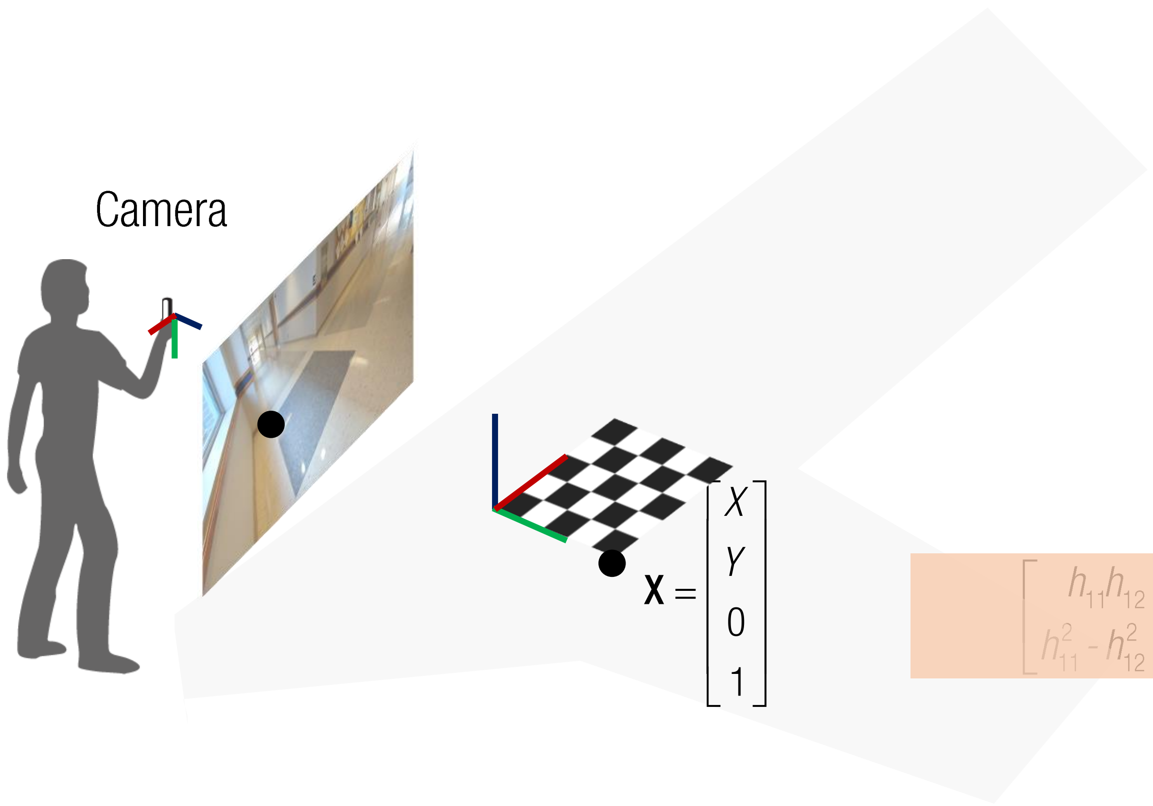
$$\begin{bmatrix} h_{11} \\ h_{21} \\ h_{31} \end{bmatrix}^T \begin{bmatrix} b_1 & & b_2 \\ & b_1 & b_3 \\ b_2 & b_3 & b_4 \end{bmatrix} \begin{bmatrix} h_{11} \\ h_{21} \\ h_{31} \end{bmatrix} = \begin{bmatrix} h_{12} \\ h_{22} \\ h_{32} \end{bmatrix}^T \begin{bmatrix} b_1 & & b_2 \\ & b_1 & b_3 \\ b_2 & b_3 & b_4 \end{bmatrix} \begin{bmatrix} h_{12} \\ h_{22} \\ h_{32} \end{bmatrix}$$

$$\begin{bmatrix} h_{11}h_{12} + h_{21}h_{22} & h_{11}h_{32} + h_{31}h_{12} & h_{21}h_{32} + h_{31}h_{22} & h_{32}h_{31} \\ h_{11}^2 - h_{12}^2 + h_{21}^2 - h_{22}^2 & 2(h_{11}h_{31} - h_{12}h_{32}) & 2(h_{21}h_{31} - h_{22}h_{32}) & h_{31}^2 - h_{32}^2 \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} = \mathbf{0}$$

2x4

$$p_x = -\frac{b_2}{b_1}, \quad p_y = -\frac{b_3}{b_1}, \quad f = \sqrt{\frac{b_4}{b_1} - (p_x^2 + p_y^2)}$$

Method2: Rotation



$$\mathbf{h}_1^{\mathsf{T}}\mathbf{B}\mathbf{h}_2 = \begin{bmatrix} h_{11} \\ h_{21} \\ h_{31} \end{bmatrix}^{\mathsf{T}} \begin{bmatrix} b_1 & & b_2 \\ & b_1 & b_3 \\ b_2 & b_3 & b_4 \end{bmatrix} \begin{bmatrix} h_{12} \\ h_{22} \\ h_{32} \end{bmatrix} = 0$$

$$\mathbf{h}_1^{\mathsf{T}}\mathbf{B}\mathbf{h}_1 = \mathbf{h}_2^{\mathsf{T}}\mathbf{B}\mathbf{h}_2$$

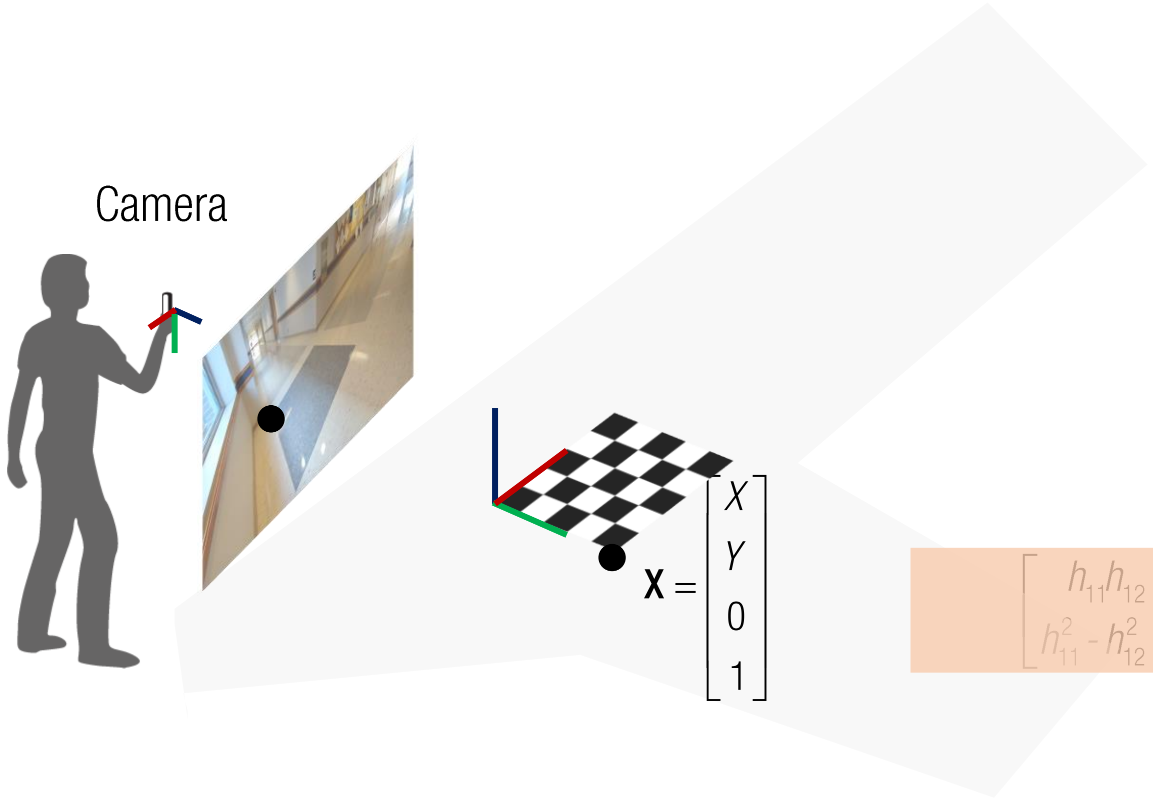
$$\begin{bmatrix} h_{11} \\ h_{21} \\ h_{31} \end{bmatrix}^{\mathsf{T}} \begin{bmatrix} b_1 & & b_2 \\ & b_1 & b_3 \\ b_2 & b_3 & b_4 \end{bmatrix} \begin{bmatrix} h_{11} \\ h_{21} \\ h_{31} \end{bmatrix} = \begin{bmatrix} h_{12} \\ h_{22} \\ h_{32} \end{bmatrix}^{\mathsf{T}} \begin{bmatrix} b_1 & & b_2 \\ & b_1 & b_3 \\ b_2 & b_3 & b_4 \end{bmatrix} \begin{bmatrix} h_{12} \\ h_{22} \\ h_{32} \end{bmatrix}$$

$$\underbrace{\begin{bmatrix} h_{11}h_{12} + h_{21}h_{22} & h_{11}h_{32} + h_{31}h_{12} & h_{21}h_{32} + h_{31}h_{22} & h_{32}h_{31} \\ h_{11}^2 - h_{12}^2 + h_{21}^2 - h_{22}^2 & 2(h_{11}h_{31} - h_{12}h_{32}) & 2(h_{21}h_{31} - h_{22}h_{32}) & h_{31}^2 - h_{32}^2 \end{bmatrix}}_{\mathbf{A}} \underbrace{\begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix}}_{\mathbf{x}} = \mathbf{0}$$

2x4

Each image produces 2 equations and therefore, **x** can be computed with minimum 2 images.

Method2: Rotation



$$\mathbf{X} = \begin{bmatrix} X \\ Y \\ 0 \\ 1 \end{bmatrix}$$

$$\mathbf{h}_1^{\mathsf{T}}\mathbf{B}\mathbf{h}_2 = \begin{bmatrix} h_{11} \\ h_{21} \\ h_{31} \end{bmatrix}^{\mathsf{T}} \begin{bmatrix} b_1 & & b_2 \\ & b_1 & b_3 \\ b_2 & b_3 & b_4 \end{bmatrix} \begin{bmatrix} h_{12} \\ h_{22} \\ h_{32} \end{bmatrix} = 0$$

$$\mathbf{h}_1^{\mathsf{T}}\mathbf{B}\mathbf{h}_1 = \mathbf{h}_2^{\mathsf{T}}\mathbf{B}\mathbf{h}_2$$

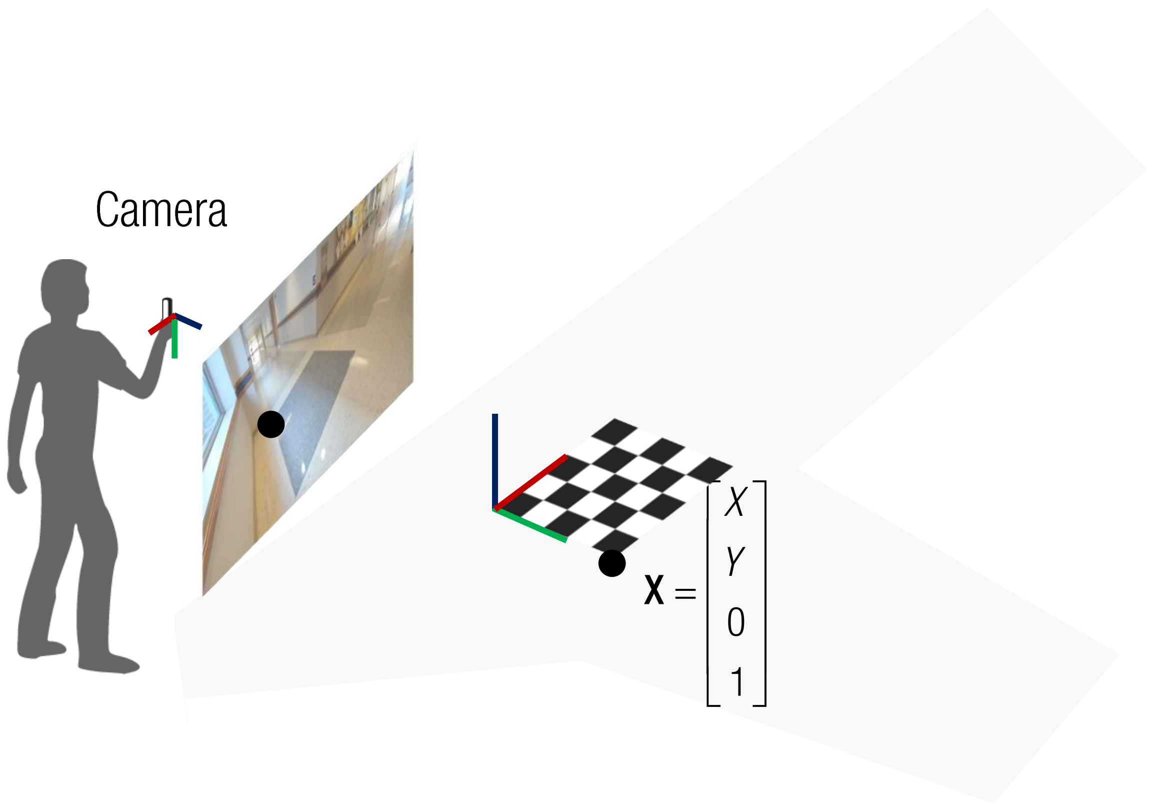
$$\begin{bmatrix} h_{11} \\ h_{21} \\ h_{31} \end{bmatrix}^{\mathsf{T}} \begin{bmatrix} b_1 & & b_2 \\ & b_1 & b_3 \\ b_2 & b_3 & b_4 \end{bmatrix} \begin{bmatrix} h_{11} \\ h_{21} \\ h_{31} \end{bmatrix} = \begin{bmatrix} h_{12} \\ h_{22} \\ h_{32} \end{bmatrix}^{\mathsf{T}} \begin{bmatrix} b_1 & & b_2 \\ & b_1 & b_3 \\ b_2 & b_3 & b_4 \end{bmatrix} \begin{bmatrix} h_{12} \\ h_{22} \\ h_{32} \end{bmatrix}$$

$$\mathbf{A}\,\mathbf{x} = \begin{bmatrix} h_{11}h_{12} + h_{21}h_{22} & h_{11}h_{32} + h_{31}h_{12} & h_{21}h_{32} + h_{31}h_{22} & h_{32}h_{31} \\ h_{11}^2 - h_{12}^2 + h_{21}^2 - h_{22}^2 & 2(h_{11}h_{31} - h_{12}h_{32}) & 2(h_{21}h_{31} - h_{22}h_{32}) & h_{31}^2 - h_{32}^2 \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} = 0$$

2x4

$$p_x = -\frac{b_2}{b_1}, \quad p_y = -\frac{b_3}{b_1}, \quad f = \sqrt{\frac{b_4}{b_1} - (p_x^2 + p_y^2)}$$

Method2: Rotation



: Knowns

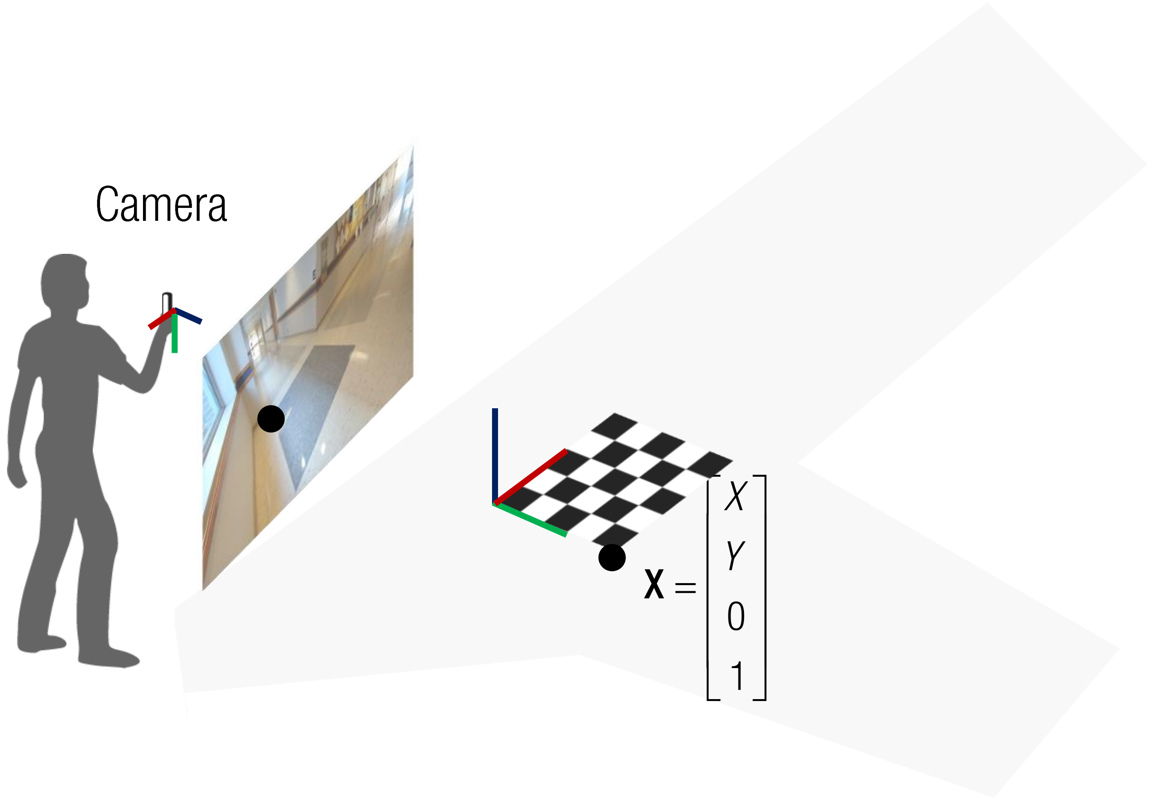
: Unknowns

Homography factorization:

$$\left(\begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix}\right)^{-1} \begin{bmatrix} \mathbf{h}_1 & \mathbf{h}_2 & \mathbf{h}_3 \end{bmatrix} = \begin{bmatrix} \mathbf{r}_1 & \mathbf{r}_2 & \mathbf{t} \end{bmatrix}$$

$$\mathbf{r}_1 = \mathbf{K}^{-1}\mathbf{h}_1 \qquad \mathbf{r}_2 = \mathbf{K}^{-1}\mathbf{h}_2 \qquad \mathbf{r}_3 = \mathbf{K}^{-1}\mathbf{h}_3$$

Method2: Rotation



$$\mathbf{X} = \begin{bmatrix} X \\ Y \\ 0 \\ 1 \end{bmatrix}$$

: Knowns

: Unknowns

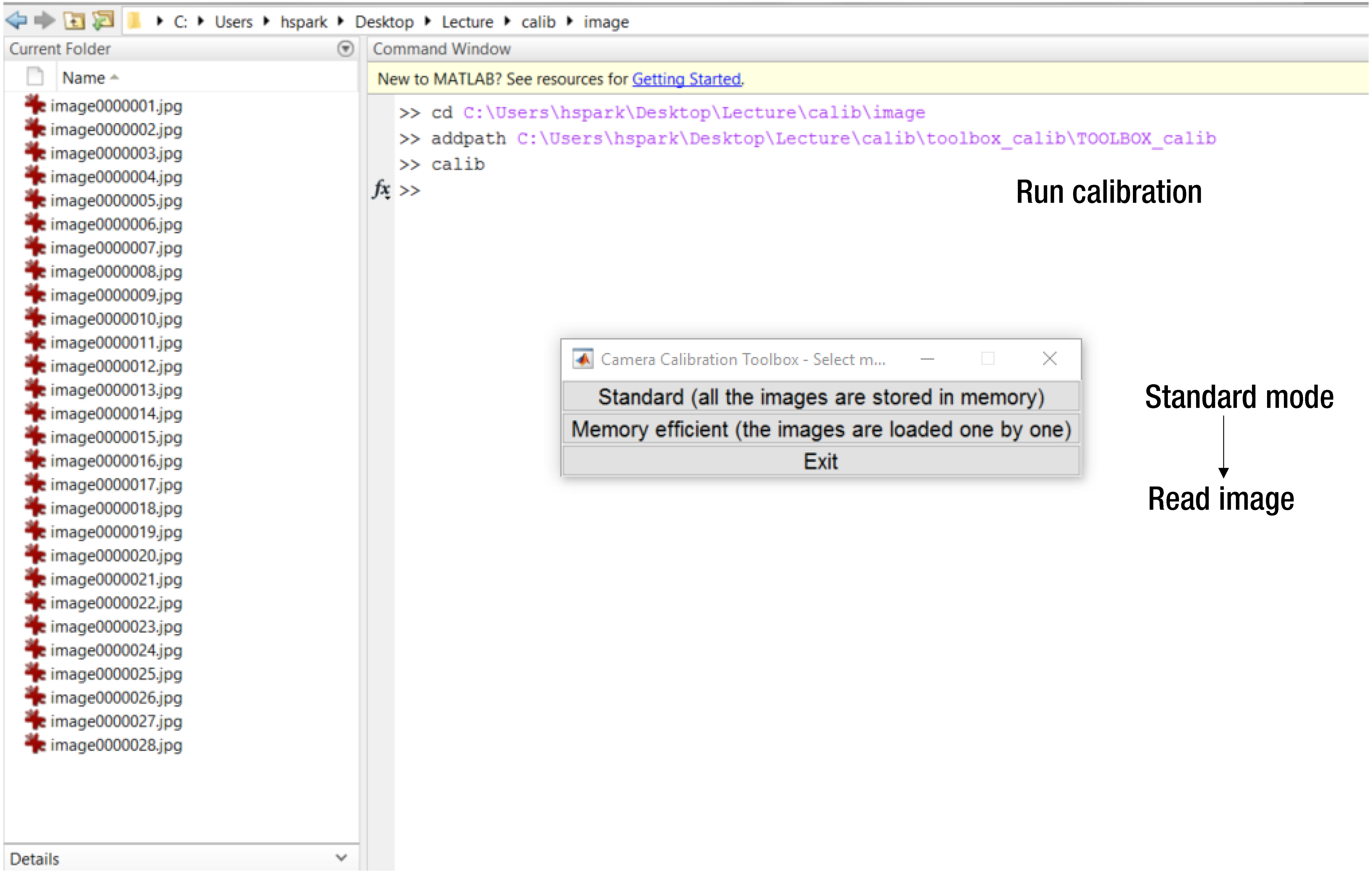
Homography factorization:

$$\left(\begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix}\right)^{-1} \begin{bmatrix} \mathbf{h}_1 & \mathbf{h}_2 & \mathbf{h}_3 \end{bmatrix} = \begin{bmatrix} \mathbf{r}_1 & \mathbf{r}_2 & \mathbf{t} \end{bmatrix}$$

$$\mathbf{r}_1 = \mathbf{K}^{-1}\mathbf{h}_1 \qquad \mathbf{r}_2 = \mathbf{K}^{-1}\mathbf{h}_2 \qquad \mathbf{r}_3 = \mathbf{K}^{-1}\mathbf{h}_3$$

$$\mathbf{r}_1 = \frac{\mathbf{K}^{-1}\mathbf{h}_1}{\left\|\mathbf{K}^{-1}\mathbf{h}_1\right\|}, \quad \mathbf{r}_2 = \frac{\mathbf{K}^{-1}\mathbf{h}_2}{\left\|\mathbf{K}^{-1}\mathbf{h}_1\right\|}, \quad \mathbf{t} = \frac{\mathbf{K}^{-1}\mathbf{h}_3}{\left\|\mathbf{K}^{-1}\mathbf{h}_1\right\|}, \quad \mathbf{r}_3 = \mathbf{r}_1 \times \mathbf{r}_2$$

Divided by constant factor



Run calibration

Standard mode

↓

Read image

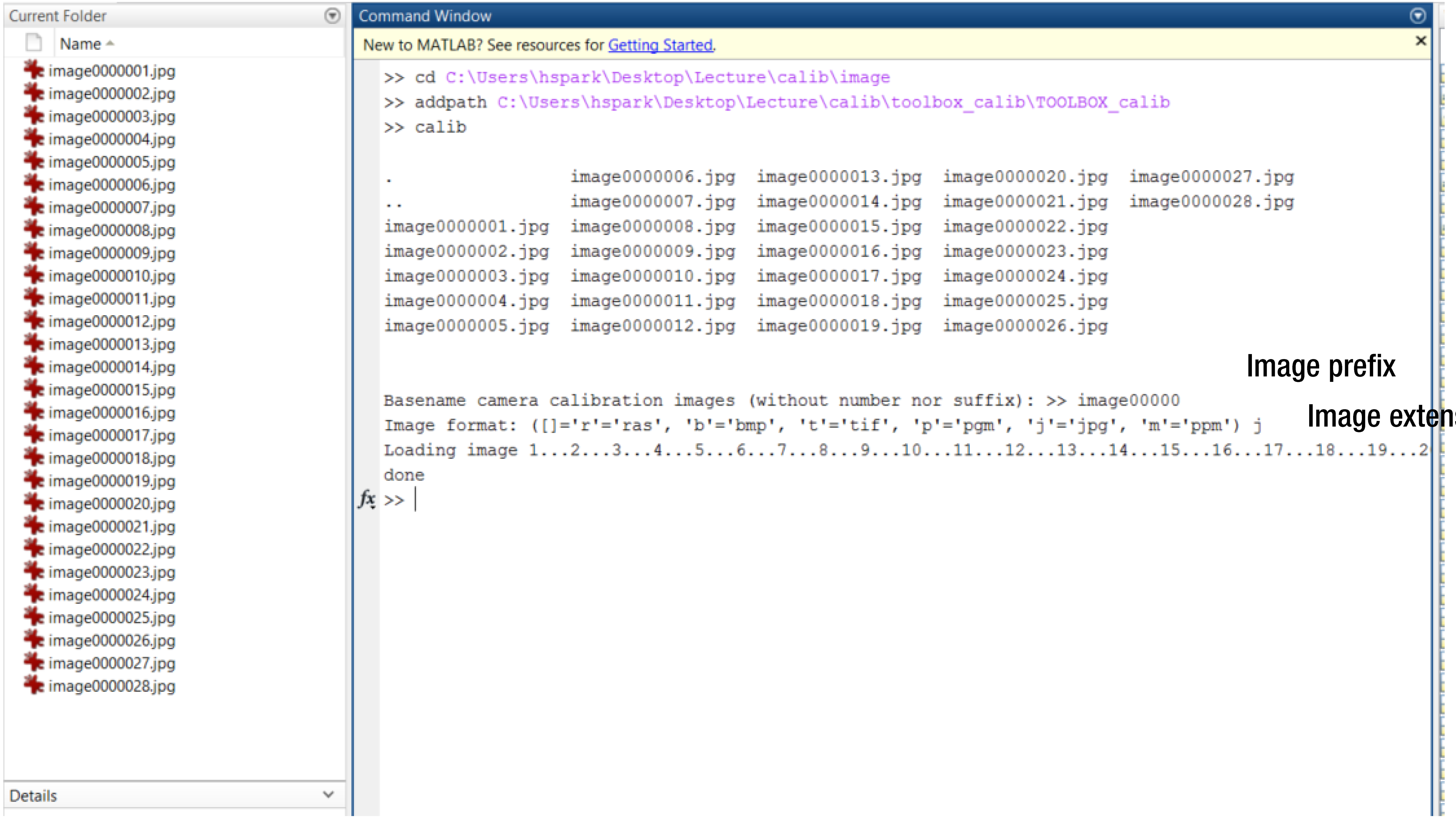

Current Folder
Name
image0000001.jpg
image0000002.jpg
image0000003.jpg
image0000004.jpg
image0000005.jpg
image0000006.jpg
image0000007.jpg
image0000008.jpg
image0000009.jpg
image0000010.jpg
image0000011.jpg
image0000012.jpg
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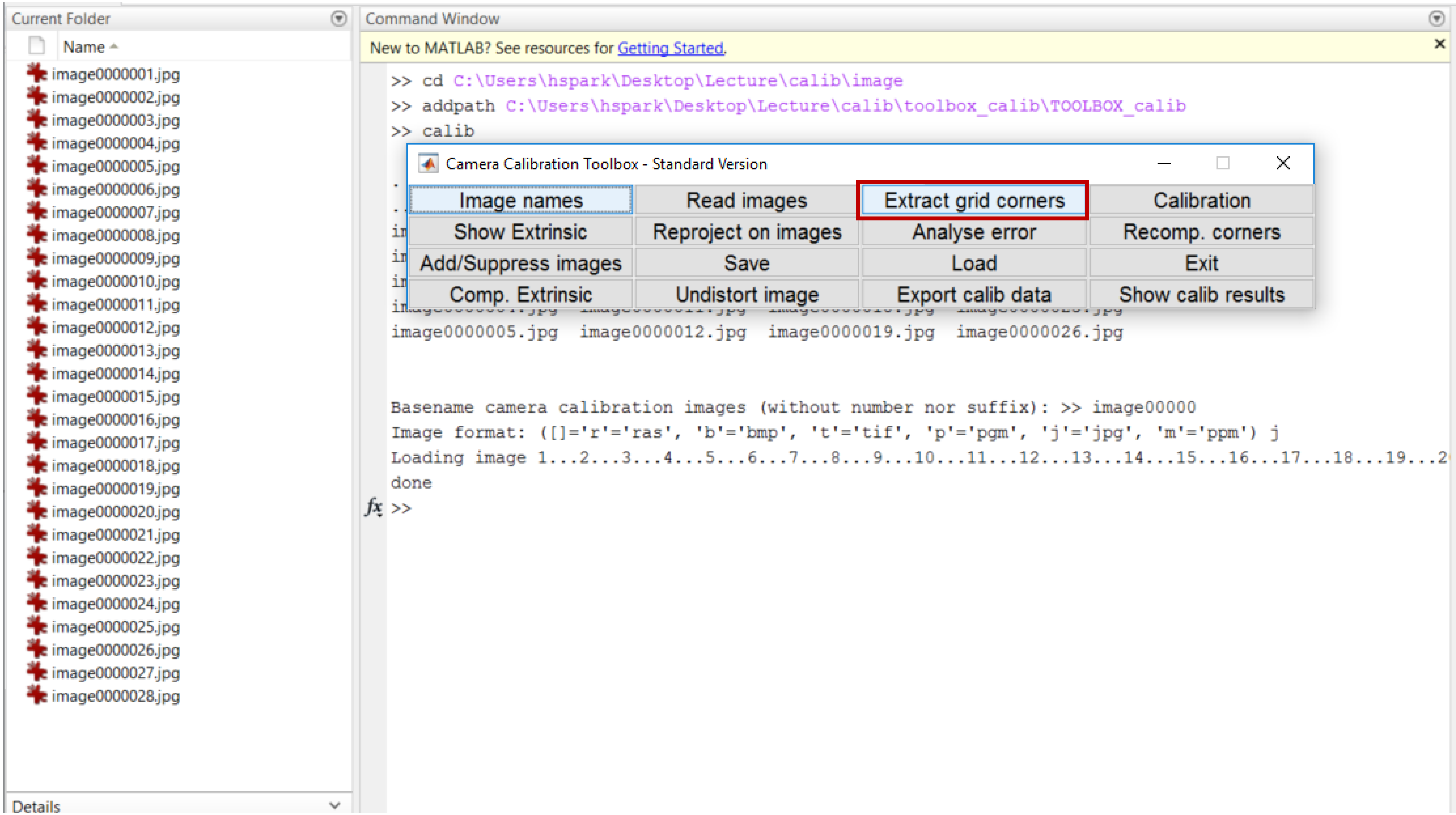
image0000020.jpg
image0000021.jpg
image0000022.jpg
image0000023.jpg
image0000024.jpg
image0000025.jpg
image0000026.jpg
image0000027.jpg
image0000028.jpg
Details
Command Window
New to MATLAB? See resources for Getting Started.
>> cd C:\Users\hspark\Desktop\Lecture\calib\image
>> addpath C:\Users\hspark\Desktop\Lecture\calib\toolbox_calib\TOOLBOX_calib
>> calib
. image0000006.jpg image0000013.jpg image0000020.jpg image0000027.jpg
.. image0000007.jpg image0000014.jpg image0000021.jpg image0000028.jpg
image0000001.jpg image0000008.jpg image0000015.jpg image0000022.jpg
image0000002.jpg image0000009.jpg image0000016.jpg image0000023.jpg
image0000003.jpg image0000010.jpg image0000017.jpg image0000024.jpg
image0000004.jpg image0000011.jpg image0000018.jpg image0000025.jpg
image0000005.jpg image0000012.jpg image0000019.jpg image0000026.jpg
Basename camera calibration images (without number nor suffix): >> image00000
Image format: ([]='r'='ras', 'b'='bmp', 't'='tif', 'p'='pgm', 'j'='jpg', 'm'='ppm') j
Loading image 1...2...3...4...5...6...7...8...9...10...11...12...13...14...15...16...17...18...19...2
done
>>
Image prefix
Image extension



Current Folder
Name
image0000001.jpg
image0000002.jpg
image0000003.jpg
image0000004.jpg
image0000005.jpg
image0000006.jpg
image0000007.jpg
image0000008.jpg
image0000009.jpg
image0000010.jpg
image0000011.jpg
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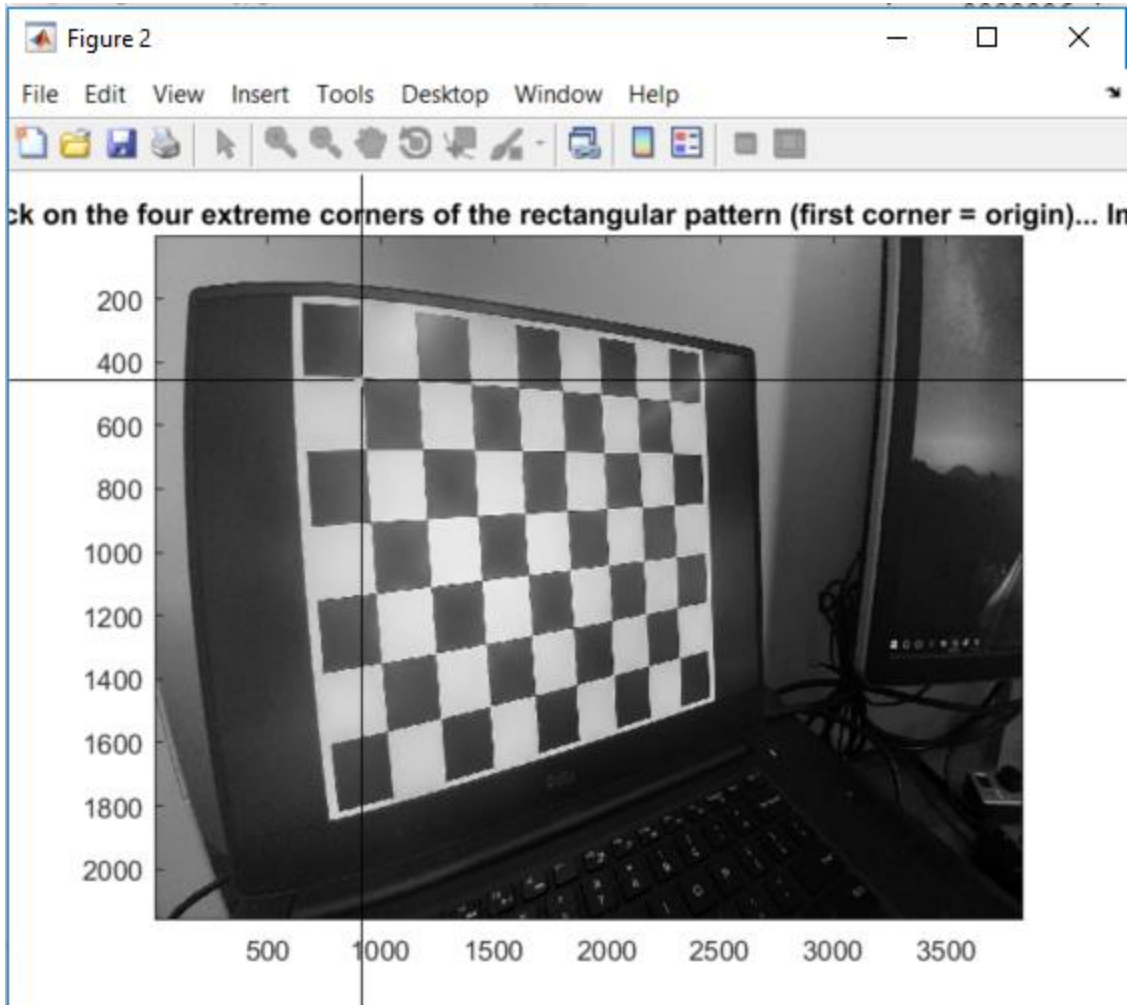
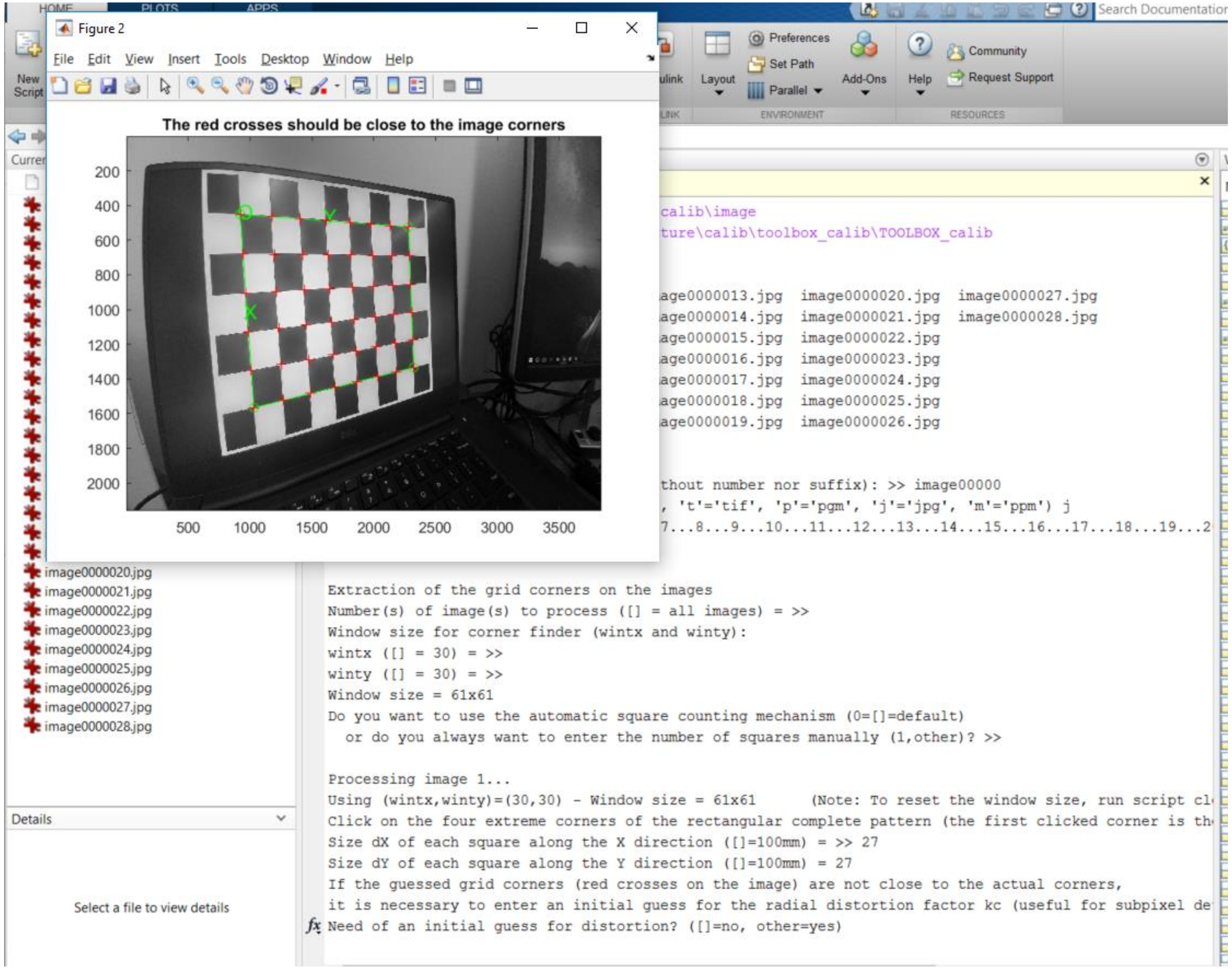
image0000014.jpg
image0000015.jpg
image0000016.jpg
image0000017.jpg
image0000018.jpg
image0000019.jpg
image0000020.jpg
image0000021.jpg
image0000022.jpg
image0000023.jpg
image0000024.jpg
image0000025.jpg
image0000026.jpg
image0000027.jpg
image0000028.jpg
Details
Command Window
New to MATLAB? See resources for Getting Started.
>> cd C:\Users\hspark\Desktop\Lecture\calib\image
>> addpath C:\Users\hspark\Desktop\Lecture\calib\toolbox_calib\TOOLBOX_calib
>> calib
Camera Calibration Toolbox - Standard Version
Image names
Read images
Extract grid corners
Calibration
Show Extrinsic
Reproject on images
Analyse error
Recomp. corners
Add/Suppress images
Save
Load
Exit
Comp. Extrinsic
Undistort image
Export calib data
Show calib results
image0000005.jpg image0000012.jpg image0000019.jpg image0000026.jpg
Basename camera calibration images (without number nor suffix): >> image00000
Image format: ([]='r'='ras', 'b'='bmp', 't'='tif', 'p'='pgm', 'j'='jpg', 'm'='ppm') j
Loading image 1...2...3...4...5...6...7...8...9...10...11...12...13...14...15...16...17...18...19...2
done
>>



Click four corner in the following order:

1. Top left
2. Top right
3. Bottom right
4. Bottom left



Default mode (press Enter)

Set grid size (27mm)

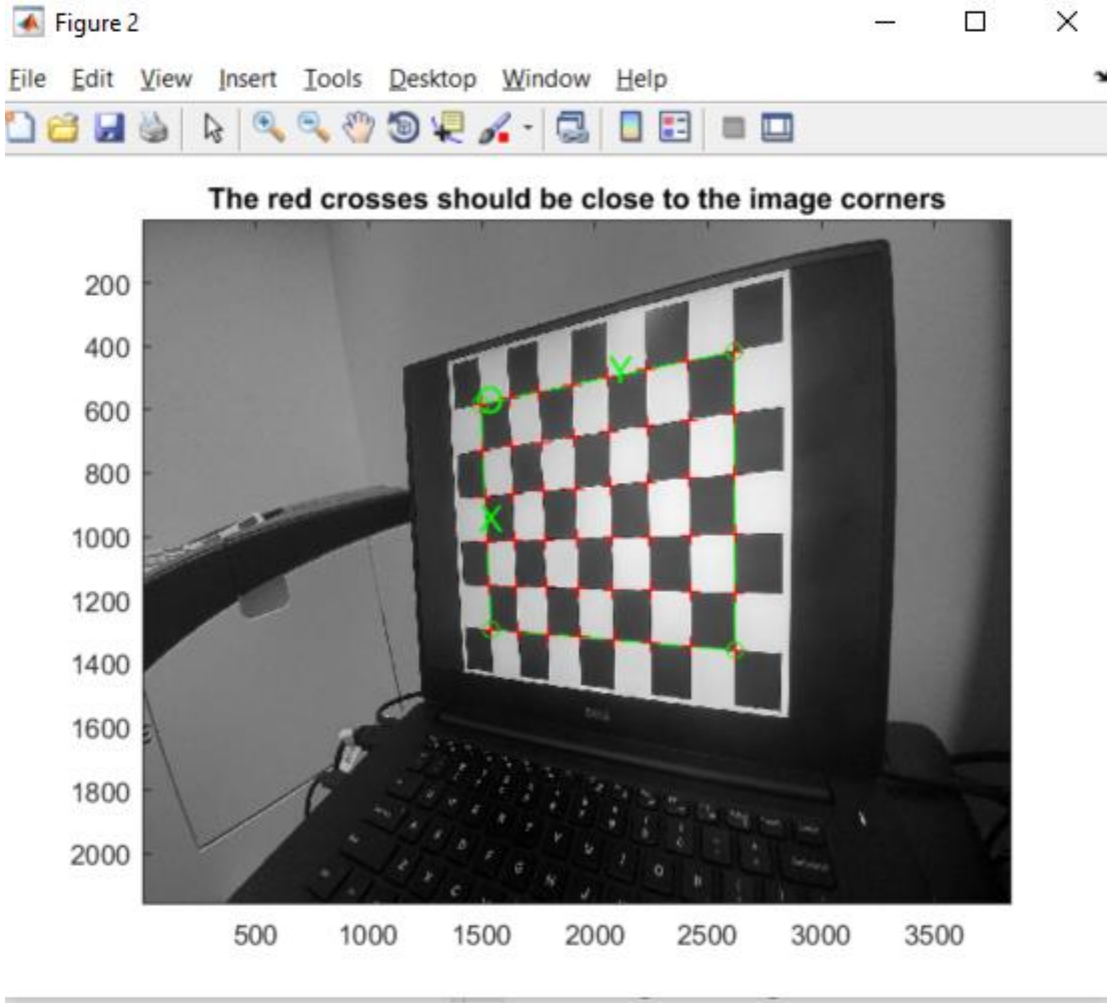
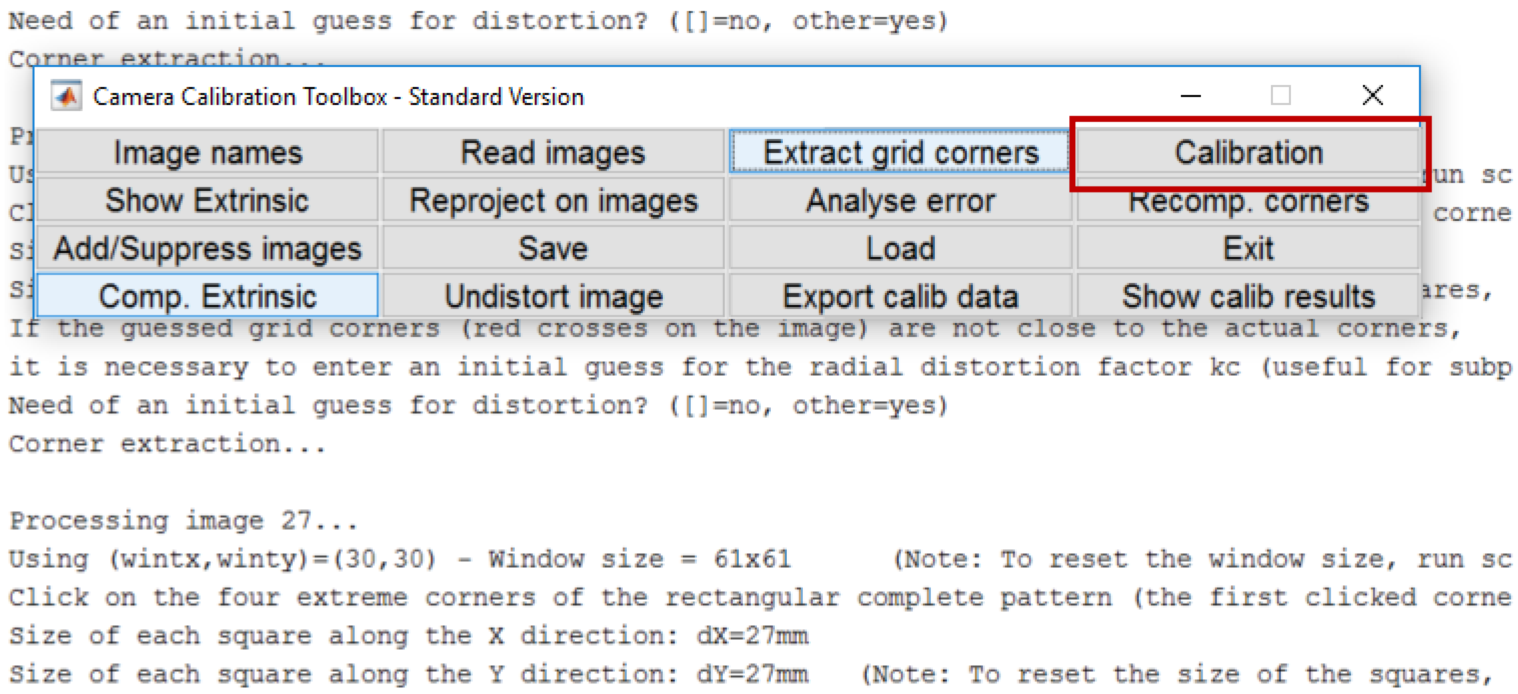


Figure 2
File Edit View Insert Tools Desktop Window Help
The red crosses should be close to the image corners
200
400
600
800
1000
1200
1400
1600
1800
2000
500
1000
1500
2000
2500
3000
3500
O
X
Y


Need of an initial guess for distortion? ([]=no, other=yes)
Corner extraction...
Camera Calibration Toolbox - Standard Version
Image names
Read images
Extract grid corners
Calibration
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Undistort image
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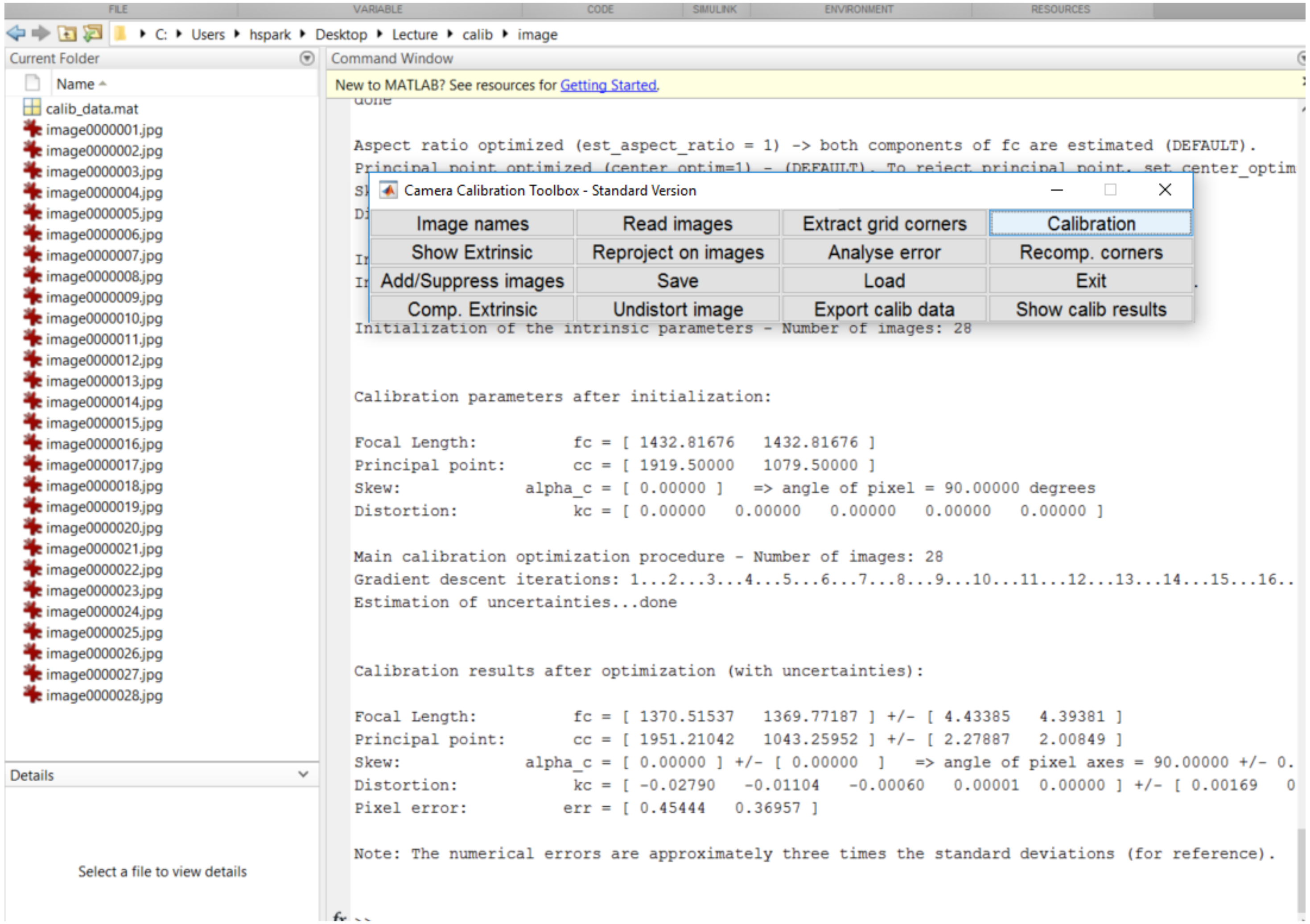
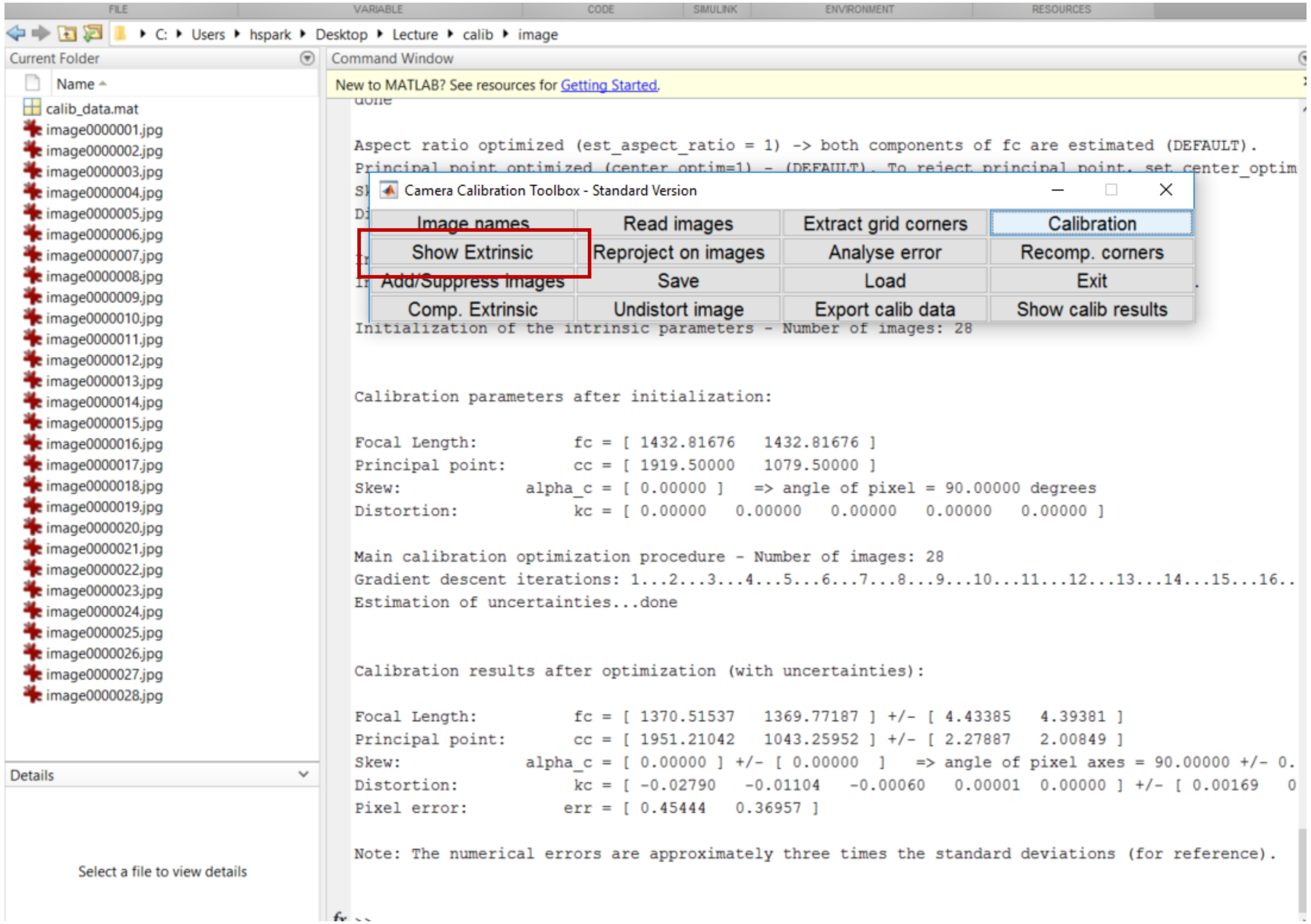
If the guessed grid corners (red crosses on the image) are not close to the actual corners,
it is necessary to enter an initial guess for the radial distortion factor kc (useful for subp
Need of an initial guess for distortion? ([]=no, other=yes)
Corner extraction...
Processing image 27...
Using (wintx,winty)=(30,30) - Window size = 61x61 (Note: To reset the window size, run sc
Click on the four extreme corners of the rectangular complete pattern (the first clicked corne
Size of each square along the X direction: dX=27mm
Size of each square along the Y direction: dY=27mm (Note: To reset the size of the squares,

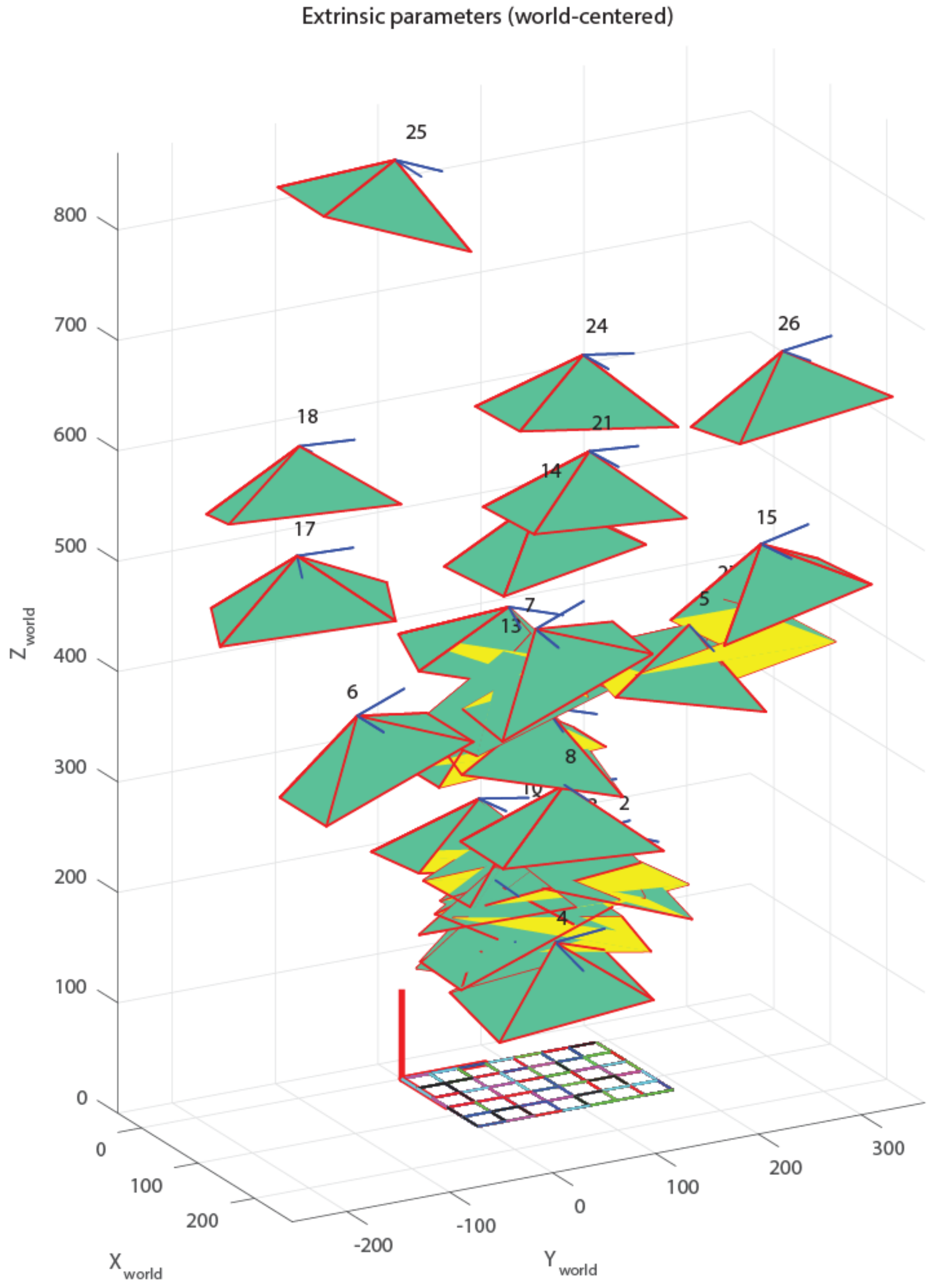


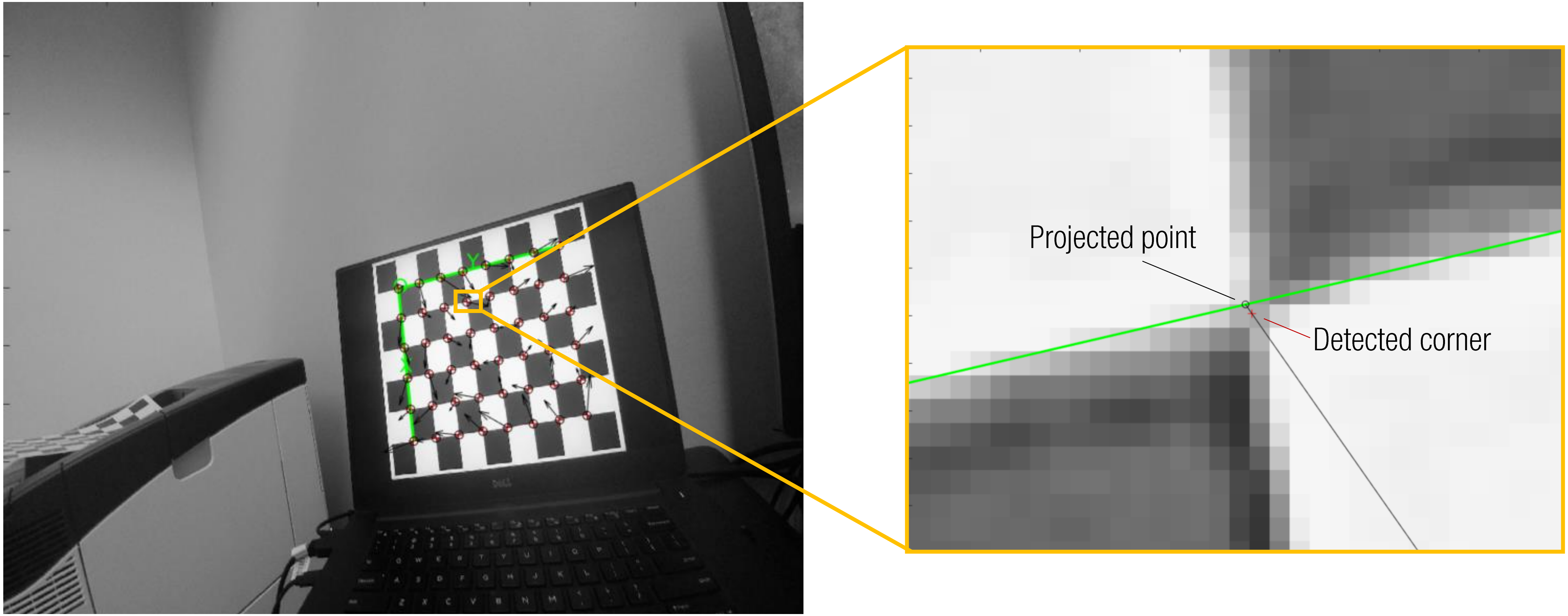
Cf) calibration with vanishing points

K =

1317.2	0	1931.8
0	1317.2	1146.1
0	0	1


FILE
VARIABLE
CODE
SIMULINK
ENVIRONMENT
RESOURCES
C: ▸ Users ▸ hspark ▸ Desktop ▸ Lecture ▸ calib ▸ image
Current Folder
Name
calib_data.mat
image0000001.jpg
image0000002.jpg
image0000003.jpg
image0000004.jpg
image0000005.jpg
image0000006.jpg
image0000007.jpg
image0000008.jpg
image0000009.jpg
image0000010.jpg
image0000011.jpg
image0000012.jpg
image0000013.jpg
image0000014.jpg
image0000015.jpg
image0000016.jpg
image0000017.jpg
image0000018.jpg
image0000019.jpg
image0000020.jpg
image0000021.jpg
image0000022.jpg
image0000023.jpg
image0000024.jpg
image0000025.jpg
image0000026.jpg
image0000027.jpg
image0000028.jpg
Details
Select a file to view details
Command Window
New to MATLAB? See resources for Getting Started.
Aspect ratio optimized (est_aspect_ratio = 1) -> both components of fc are estimated (DEFAULT).
Camera Calibration Toolbox - Standard Version
Image names
Read images
Extract grid corners
Calibration
Show Extrinsic
Reproject on images
Analyse error
Recomp. corners
Add/Suppress images
Save
Load
Exit
Comp. Extrinsic
Undistort image
Export calib data
Show calib results
Initialization of the intrinsic parameters - Number of images: 28
Calibration parameters after initialization:
Focal Length: fc = [1432.81676 1432.81676]
Principal point: cc = [1919.50000 1079.50000]
Skew: alpha_c = [0.00000] => angle of pixel = 90.00000 degrees
Distortion: kc = [0.00000 0.00000 0.00000 0.00000 0.00000]
Main calibration optimization procedure - Number of images: 28
Gradient descent iterations: 1...2...3...4...5...6...7...8...9...10...11...12...13...14...15...16..
Estimation of uncertainties...done
Calibration results after optimization (with uncertainties):
Focal Length: fc = [1370.51537 1369.77187] +/- [4.43385 4.39381]
Principal point: cc = [1951.21042 1043.25952] +/- [2.27887 2.00849]
Skew: alpha_c = [0.00000] +/- [0.00000] => angle of pixel axes = 90.00000 +/- 0.
Distortion: kc = [-0.02790 -0.01104 -0.00060 0.00001 0.00000] +/- [0.00169 0
Pixel error: err = [0.45444 0.36957]
Note: The numerical errors are approximately three times the standard deviations (for reference).


Extrinsic parameters (world-centered)
Z_{world}
X_{world}
Y_{world}


Projected point
Detected corner