

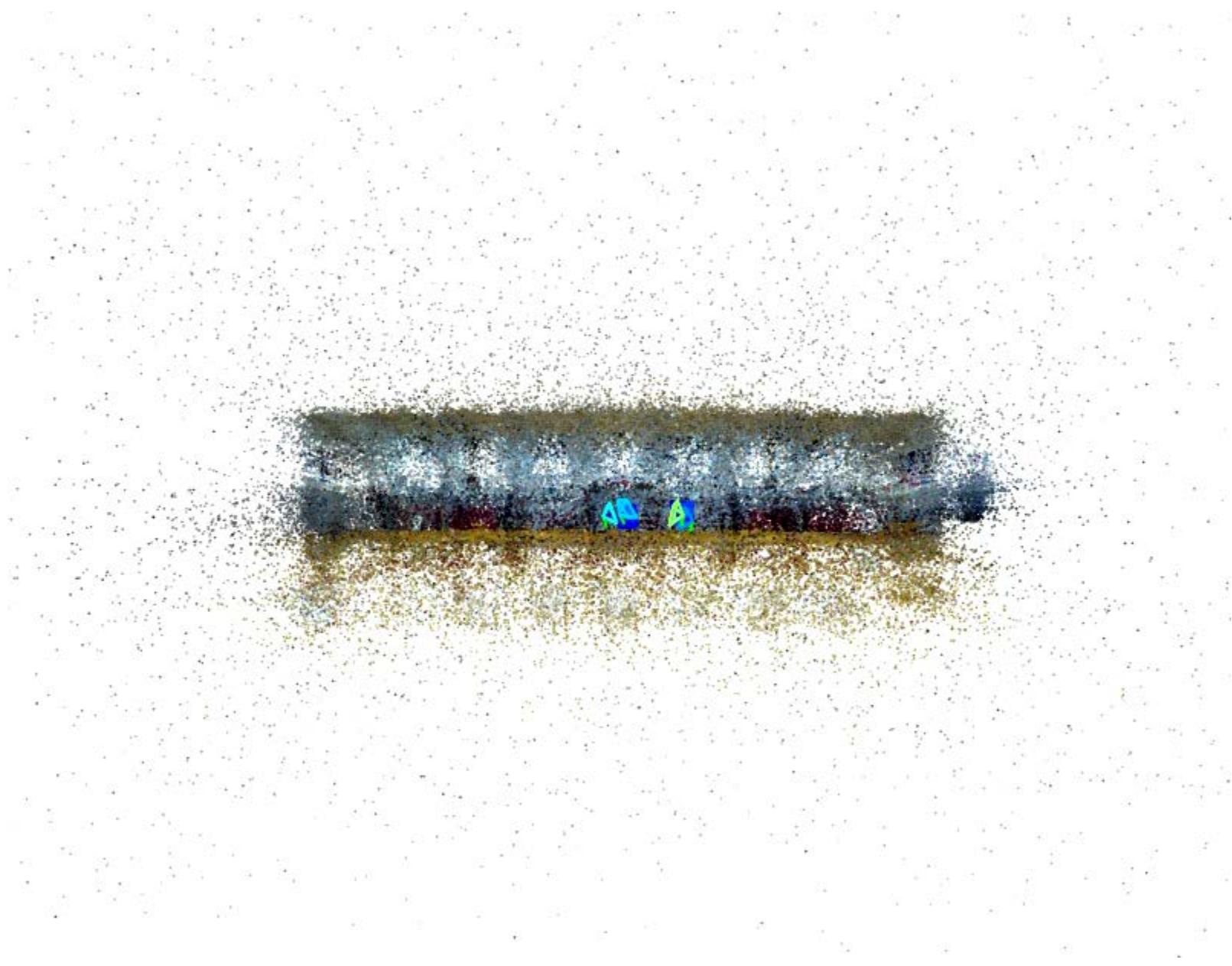


# Structure from Motion Pipeline

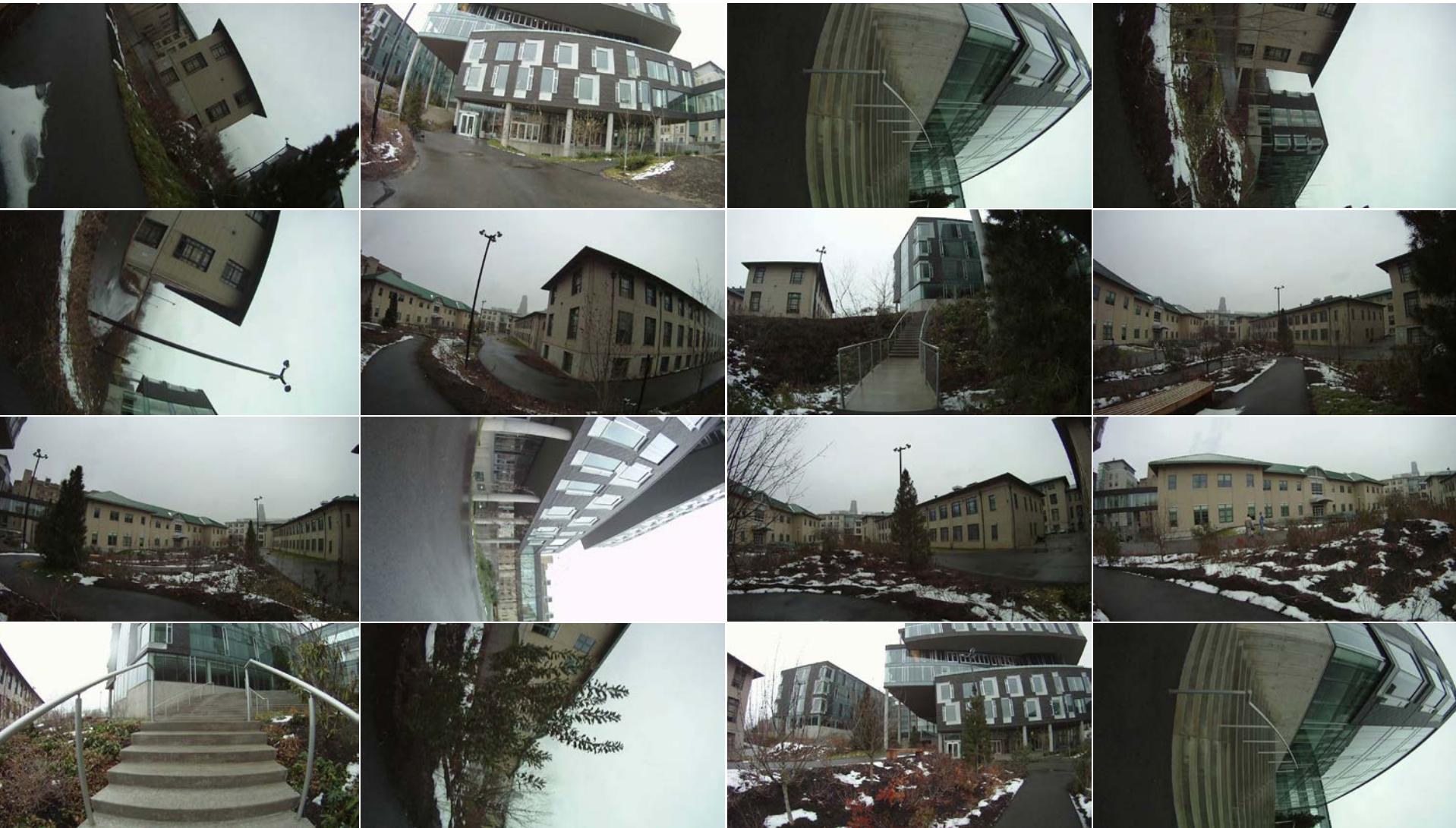


Where am I (camera)?  
Where are they (points)?

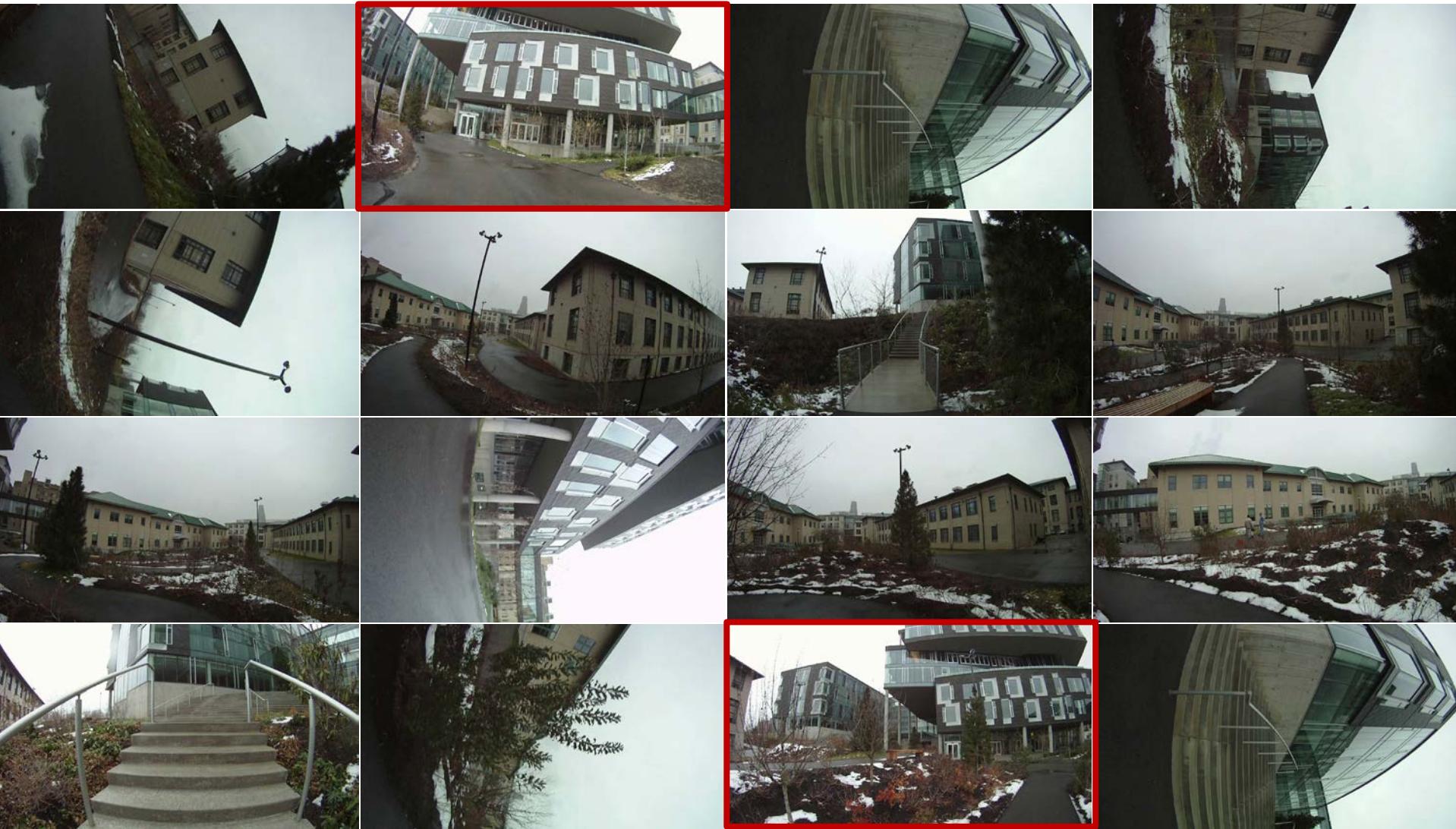




# Input Images



# Initial Pair Images



# 1. Pairwise Image Feature Matching



$$x_2^T F x_1 = 0 : \text{Fundamental matrix}$$
$$\text{where } F = K^{-T} E K^{-1}$$

$$P_1 = K [I_{3 \times 3} \quad 0]$$

$$P_2 = K [R \quad t]$$

# 1. Pairwise Image Feature Matching



$\mathbf{x}_1$

$\mathbf{x}_2$

$$\mathbf{x}_2^T \mathbf{F} \mathbf{x}_1 = 0$$

---

Epipolar constraint

# 1. Pairwise Image Feature Matching



$\mathbf{x}_1$

$$\frac{\mathbf{x}_2^T \mathbf{F} \mathbf{x}_1 = 0}{\text{Epipolar constraint}}$$

$\mathbf{x}_2$

# of unknowns: 8  
# of required equations: 8

# 1. Pairwise Image Feature Matching



$\mathbf{x}_1$

$$\frac{\mathbf{x}_2^T \mathbf{F} \mathbf{x}_1 = 0}{\text{Epipolar constraint}}$$

$\mathbf{x}_2$

# of unknowns: 8  
# of required equations: 8

$$\begin{aligned}\mathbf{x}_{2,1}^T \mathbf{F} \mathbf{x}_{1,1} &= 0 \\ &\vdots \\ \mathbf{x}_{2,8}^T \mathbf{F} \mathbf{x}_{1,8} &= 0\end{aligned}$$

# 1. Pairwise Image Feature Matching



$\mathbf{x}_1$

$$\frac{\mathbf{x}_2^T \mathbf{F} \mathbf{x}_1 = 0}{\text{Epipolar constraint}}$$

$$\begin{bmatrix} u_1^1 u_1^2 & u_1^1 v_1^2 & u_1^1 & v_1^1 u_1^2 & v_1^1 v_1^2 & v_1^1 & u_1^2 & v_1^2 & 1 \\ \vdots & \vdots \\ u_8^1 u_8^2 & u_8^1 v_8^2 & u_8^1 & v_8^1 u_8^2 & v_8^1 v_8^2 & v_8^1 & u_8^2 & v_8^2 & 1 \end{bmatrix} \mathbf{A} \begin{bmatrix} f_{11} \\ f_{21} \\ f_{31} \\ f_{12} \\ f_{23} \\ f_{31} \\ f_{32} \\ f_{33} \end{bmatrix} = 0$$

$$= 0$$

$\mathbf{x}_2$

# 8 Point Algorithm

- Construct 8x9 matrix  $\mathbf{A}$ .
- Solving linear homogeneous equations via SVD:

$$\mathbf{x} = \mathbf{V}_{:,8} \text{ where } \mathbf{A} = \mathbf{U}\mathbf{D}\mathbf{V}^T$$

$\mathbf{F} = \text{reshape}(\mathbf{x}, 3, 3)$ : constructing matrix from vector.

- Applying rank constraint, i.e.,  $\text{rank}(\mathbf{F}) = 2$ .

$$\mathbf{F}_{\text{rank2}} = \mathbf{U}\tilde{\mathbf{D}}\mathbf{V}^T \text{ where } \tilde{\mathbf{D}} : \mathbf{D} \text{ with the last element zero.}$$

$$\mathbf{F}_{\text{rank2}} = \boxed{\mathbf{U}} \quad \boxed{\tilde{\mathbf{D}}} \quad \boxed{\mathbf{V}^T}$$

$$\mathbf{F} = \boxed{\mathbf{U}} \quad \boxed{\mathbf{D}} \quad \boxed{\mathbf{V}^T}$$

---

SVD cleanup

# Epipolar Geometry



$x_1$

$$x_2^T F x_1 = 0$$

$x_2$

## 2. Outlier Rejection via RANSAC



$x_1$

$$x_2^T F x_1 = 0$$

Random sampling

Model building

Thresholding

Inlier counting

$x_2$

## 2. Outlier Rejection via RANSAC



$x_1$

$$x_2^T F x_1 = 0$$

Random sampling ←

Model building

Thresholding

Inlier counting

$x_2$

## 2. Outlier Rejection via RANSAC



$\mathbf{x}_1$

$$\mathbf{x}_2^T \mathbf{F} \mathbf{x}_1 = 0$$

Random sampling

Model building

Thresholding

Inlier counting

$\mathbf{x}_2$

## 2. Outlier Rejection via RANSAC



$\mathbf{x}_1$

$$\mathbf{x}_2^T \mathbf{F} \mathbf{x}_1 = 0$$

Random sampling

Model building

Thresholding

Inlier counting

$\mathbf{x}_2$

## 2. Outlier Rejection via RANSAC



$$\mathbf{x}_2^T \mathbf{F} \mathbf{x}_1 = 0$$

# of inliers: 253

Random sampling ←  
Model building  
Thresholding  
**Inlier counting**

The diagram shows a 3D coordinate system with three orthogonal axes: red (depth), green (vertical), and blue (horizontal). A point is shown in both frames. The transformation from frame 1 (Bob) to frame 2 (Alice) is given by the equation:

$$E = K^T F K$$

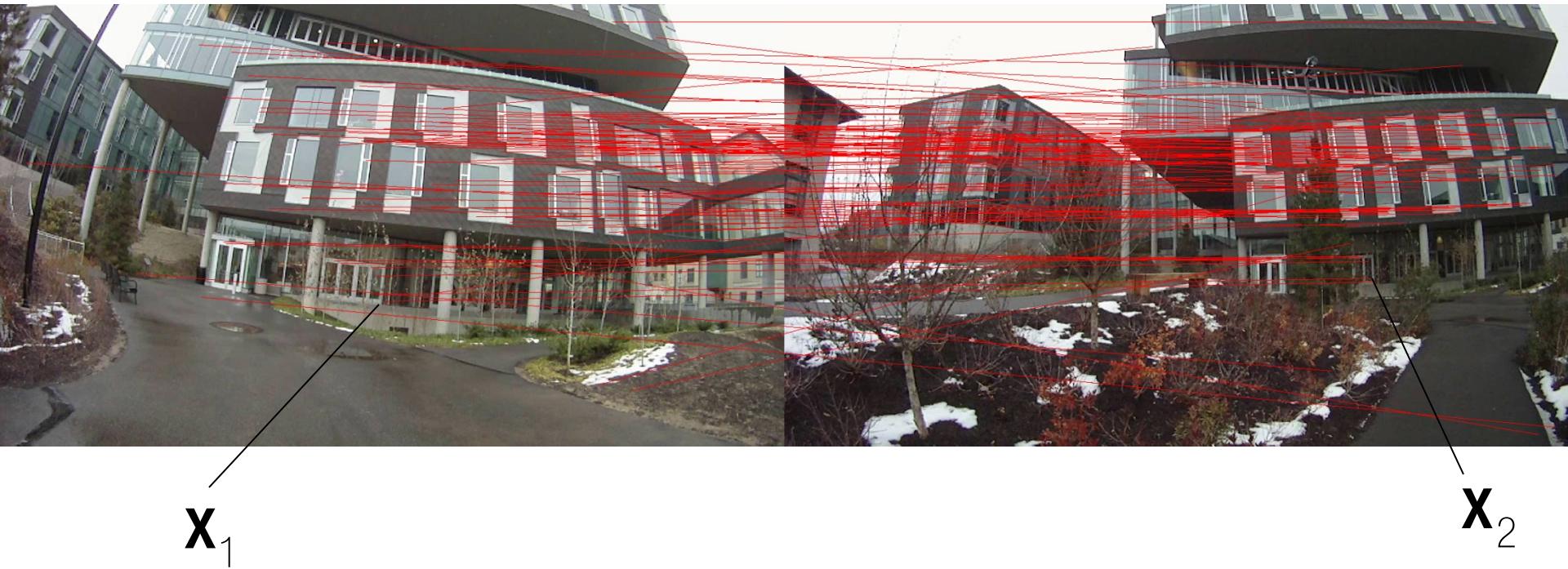
Bob

$$P_1 = K [I_{3 \times 3} \quad 0]$$

Alice

$$P_2 = K [R \quad t]$$

### 3. Essential Matrix Computation



$x_1$

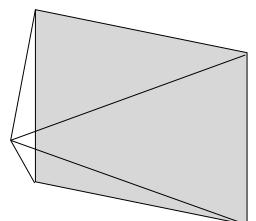
$x_2$

$$\begin{aligned} x_2^T K^{-T} E K^{-1} x_1 &= 0 \\ x_2^T F x_1 &= 0 \end{aligned} \quad \rightarrow \quad K^T F K = E$$

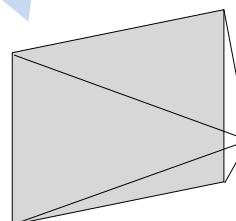
# 4. Relative Transform from Essential Matrix



$$E = [t]_x R$$



$$P_1 = [I_{3 \times 3} \mid 0_3]$$



$$P_2 = [R \mid t]$$

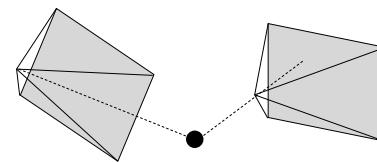
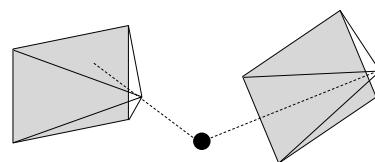
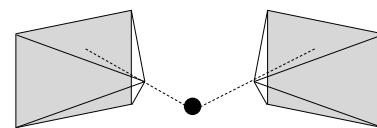
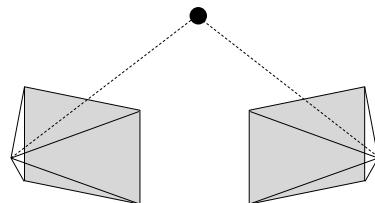
$$P_2 = [UYV^T \mid u_3]$$

$$[UY^TV^T \mid u_3]$$

$$[UYV^T \mid -u_3]$$

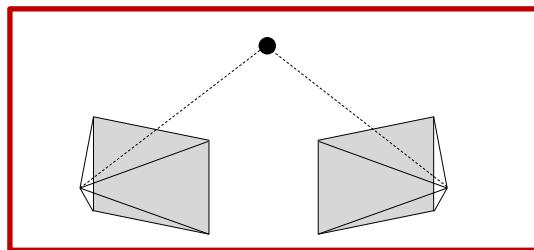
$$[UY^TV^T \mid -u_3]$$

# 4. Relative Transform from Essential Matrix

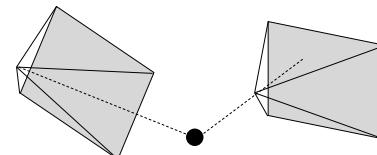
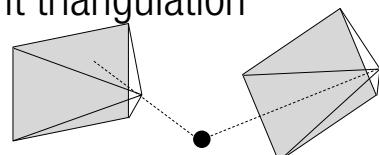
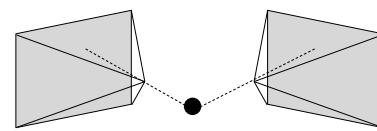


$$\begin{aligned} \mathbf{P}_2 = & \begin{bmatrix} \mathbf{U}\mathbf{Y}\mathbf{V}^T & | & \mathbf{u}_3 \end{bmatrix} \\ & \begin{bmatrix} \mathbf{U}\mathbf{Y}^T\mathbf{V}^T & | & \mathbf{u}_3 \end{bmatrix} \\ & \begin{bmatrix} \mathbf{U}\mathbf{Y}\mathbf{V}^T & | & -\mathbf{u}_3 \end{bmatrix} \\ & \begin{bmatrix} \mathbf{U}\mathbf{Y}^T\mathbf{V}^T & | & -\mathbf{u}_3 \end{bmatrix} \end{aligned}$$

# 4. Relative Transform from Essential Matrix



Correct configuration resolved via  
point triangulation



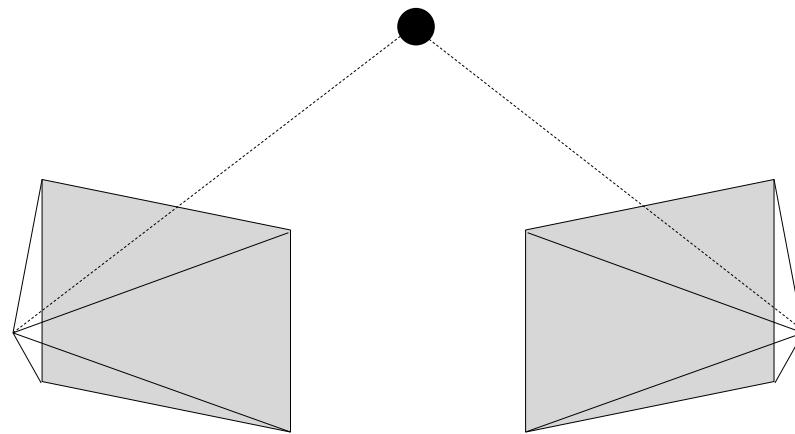
$$\mathbf{P}_2 = [\mathbf{U}\mathbf{Y}\mathbf{V}^T \mid \mathbf{u}_3]$$

$$[\mathbf{U}\mathbf{Y}^T\mathbf{V}^T \mid \mathbf{u}_3]$$

$$[\mathbf{U}\mathbf{Y}\mathbf{V}^T \mid -\mathbf{u}_3]$$

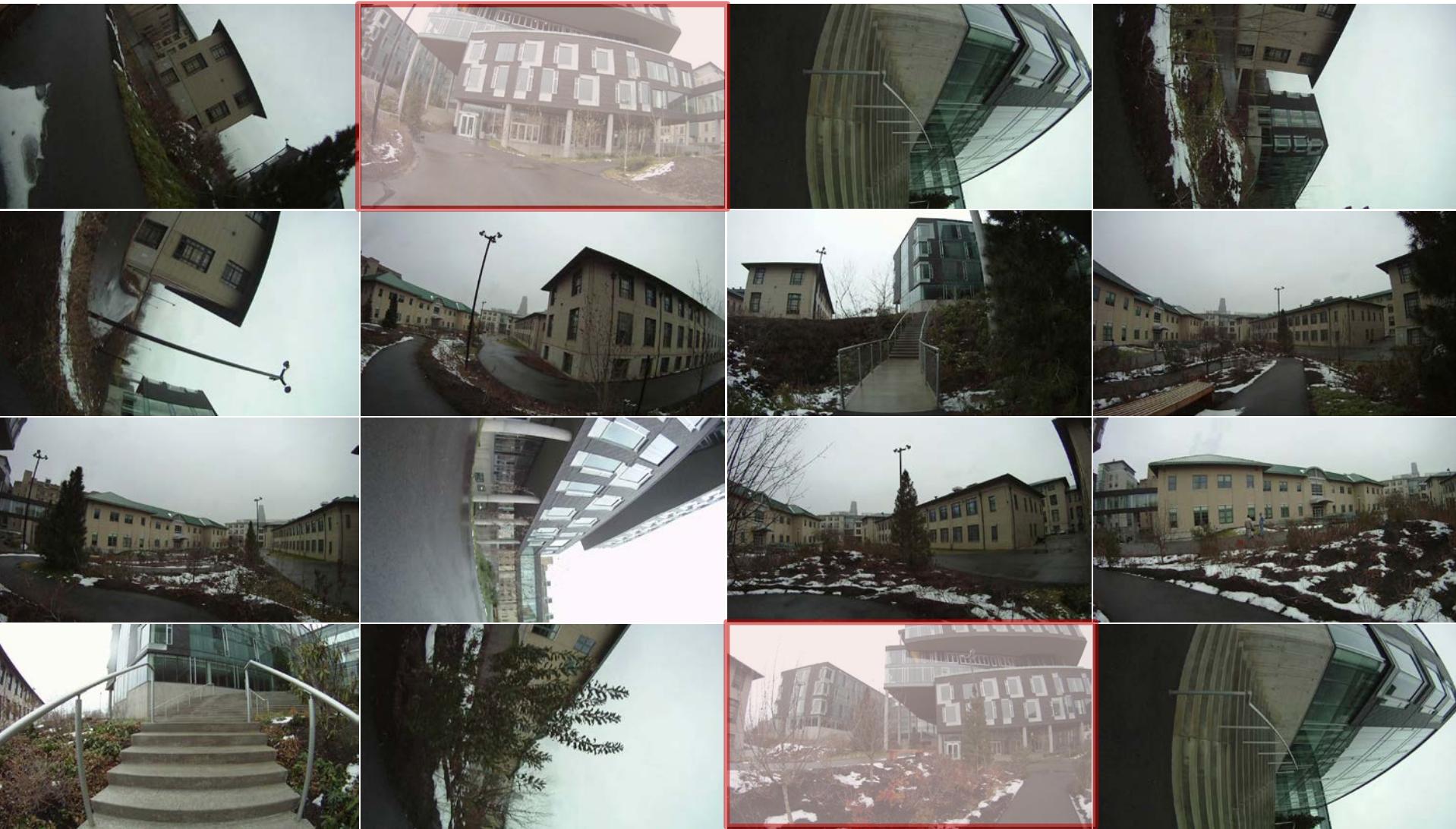
$$[\mathbf{U}\mathbf{Y}^T\mathbf{V}^T \mid -\mathbf{u}_3]$$

# 5. Point Triangulation

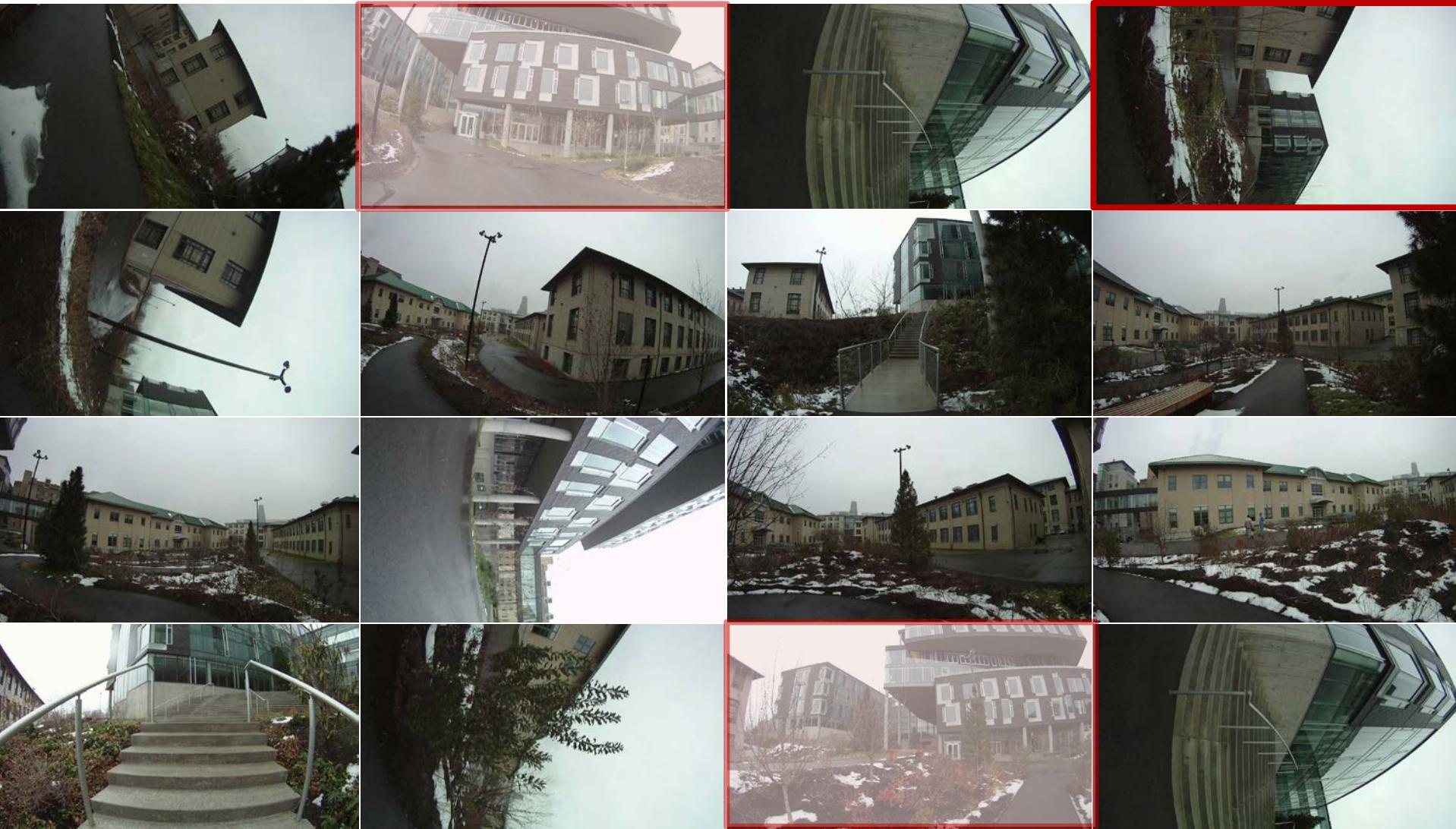


$$\begin{bmatrix} \mathbf{x}_1 \\ 1 \end{bmatrix}_{\times} \mathbf{P}_1 \\ \begin{bmatrix} \mathbf{x}_2 \\ 1 \end{bmatrix}_{\times} \mathbf{P}_2 \\ \begin{bmatrix} \mathbf{x} \\ 1 \end{bmatrix} = 0 \end{bmatrix}$$

# Initial Pair Images

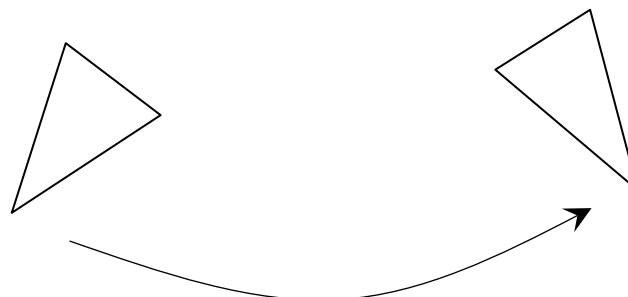
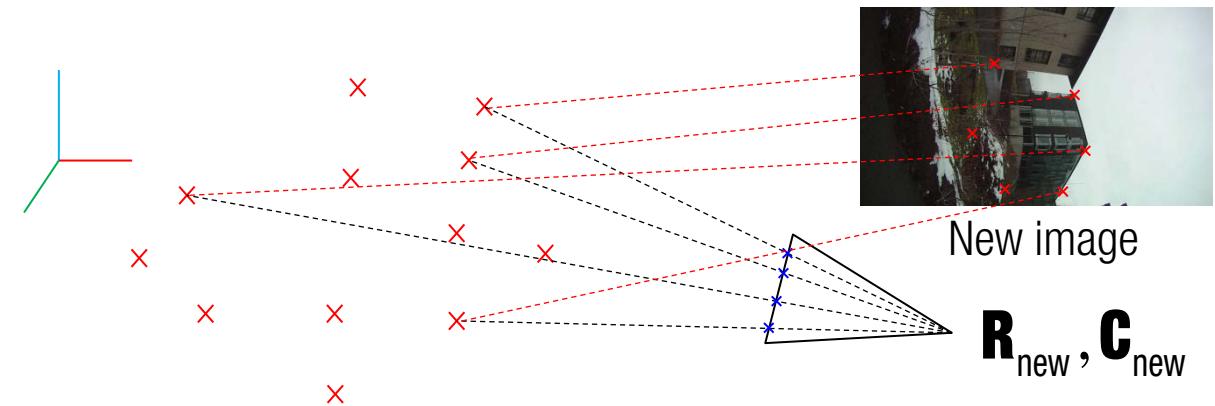


# Adding New Image



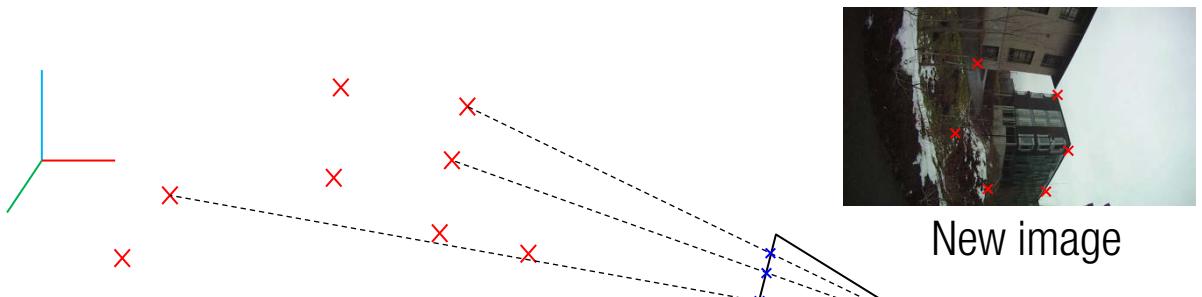
# 6. New Camera Registration

## Perspective-n-point



# 6. New Camera Registration

## Perspective-n-point

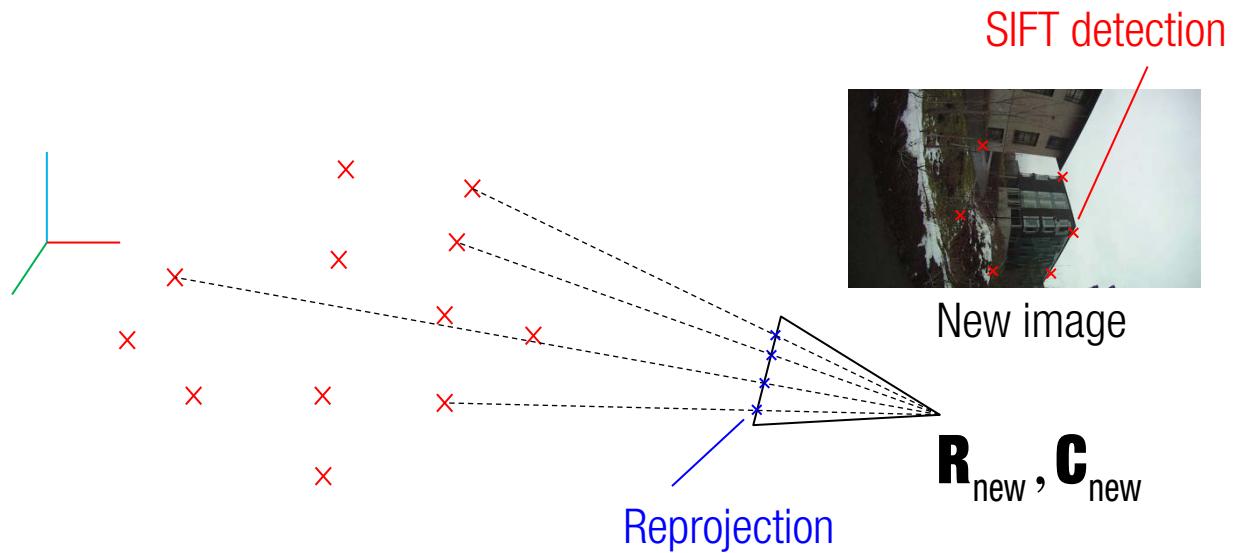


$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix}_x \begin{bmatrix} P_1 \\ P_2 \\ P_3 \end{bmatrix} \tilde{X} = \begin{bmatrix} u \\ v \\ 1 \end{bmatrix}_x \begin{bmatrix} P_1 \tilde{X} \\ P_2 \tilde{X} \\ P_3 \tilde{X} \end{bmatrix} = \begin{bmatrix} 0 & -1 & v \\ 1 & 0 & -u \\ -v & u & 0 \end{bmatrix} \begin{bmatrix} \tilde{X}^T & \mathbf{0}_{1 \times 4} & \mathbf{0}_{1 \times 4} \\ \mathbf{0}_{1 \times 4} & \tilde{X}^T & \mathbf{0}_{1 \times 4} \\ \mathbf{0}_{1 \times 4} & \mathbf{0}_{1 \times 4} & \tilde{X}^T \end{bmatrix} \begin{bmatrix} P_1^T \\ P_2^T \\ P_3^T \end{bmatrix} =$$

$$\begin{bmatrix} \mathbf{0}_{1 \times 4} & -\tilde{X}^T & v\tilde{X}^T \\ \tilde{X}^T & \mathbf{0}_{1 \times 4} & -u\tilde{X}^T \\ -v\tilde{X}^T & u\tilde{X}^T & \mathbf{0}_{1 \times 4} \end{bmatrix} \begin{bmatrix} P_1^T \\ P_2^T \\ P_3^T \end{bmatrix} = \mathbf{0}$$

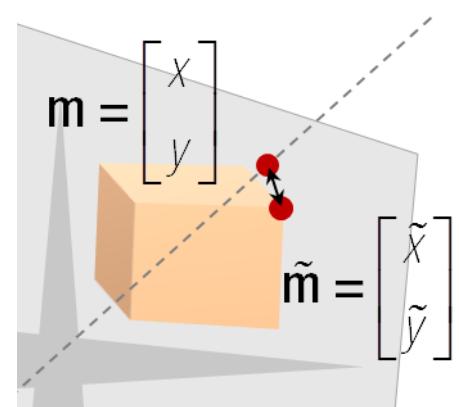
3x12 matrix

# 7. Bundle Adjustment



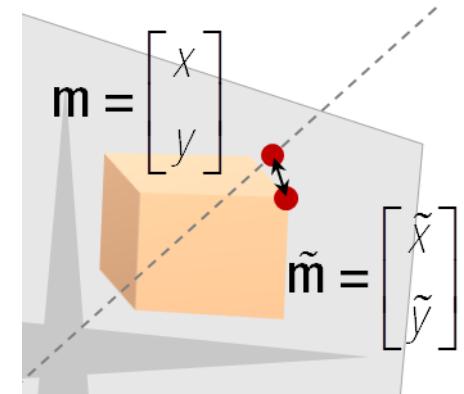
# Reprojection error

$$e = \begin{bmatrix} \tilde{x} \\ \tilde{y} \end{bmatrix} - \begin{bmatrix} u/w \\ v/w \end{bmatrix} \quad \text{where} \quad \begin{bmatrix} u \\ v \\ w \end{bmatrix} = \mathbf{P} \begin{bmatrix} \mathbf{X} \\ 1 \end{bmatrix} = \mathbf{K} \mathbf{R} [\mathbf{I}_{3 \times 3} \quad -\mathbf{C}] \begin{bmatrix} \mathbf{X} \\ 1 \end{bmatrix}$$



## Reprojection error

$$e = \begin{bmatrix} \tilde{x} \\ \tilde{y} \end{bmatrix} - \begin{bmatrix} u/w \\ v/w \end{bmatrix} \quad \text{where} \quad \begin{bmatrix} u \\ v \\ w \end{bmatrix} = \mathbf{P} \begin{bmatrix} \mathbf{X} \\ 1 \end{bmatrix} = \mathbf{K} \mathbf{R} \begin{bmatrix} \mathbf{I}_{3 \times 3} & -\mathbf{C} \end{bmatrix} \begin{bmatrix} \mathbf{X} \\ 1 \end{bmatrix}$$

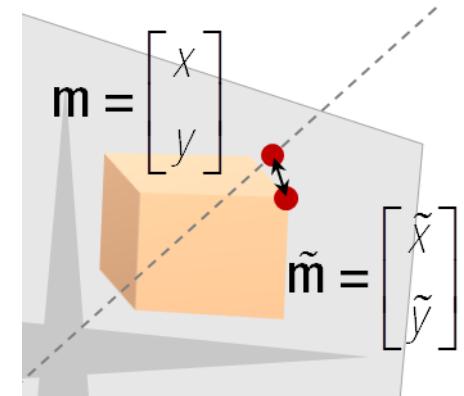


$$\underset{\mathbf{q}, \mathbf{C}, \mathbf{X}}{\text{minimize}} \left\| \begin{bmatrix} \tilde{x} \\ \tilde{y} \end{bmatrix} - \begin{bmatrix} u(\mathbf{R}(\mathbf{q}), \mathbf{C}, \mathbf{X}) / w(\mathbf{R}(\mathbf{q}), \mathbf{C}, \mathbf{X}) \\ v(\mathbf{R}(\mathbf{q}), \mathbf{C}, \mathbf{X}) / w(\mathbf{R}(\mathbf{q}), \mathbf{C}, \mathbf{X}) \end{bmatrix} \right\|^2 = \underset{\mathbf{q}, \mathbf{C}, \mathbf{X}}{\text{minimize}} \left\| \mathbf{b} - \mathbf{f}(\mathbf{R}(\mathbf{q}), \mathbf{C}, \mathbf{X}) \right\|^2$$

$$\mathbf{f}(\mathbf{R}(\mathbf{q}), \mathbf{C}, \mathbf{X}) = \begin{bmatrix} u / w \\ v / w \end{bmatrix}$$

## Reprojection error

$$e = \begin{bmatrix} \tilde{x} \\ \tilde{y} \end{bmatrix} - \begin{bmatrix} u/w \\ v/w \end{bmatrix} \quad \text{where} \quad \begin{bmatrix} u \\ v \\ w \end{bmatrix} = \mathbf{P} \begin{bmatrix} \mathbf{X} \\ 1 \end{bmatrix} = \mathbf{K} \mathbf{R} [\mathbf{I}_{3 \times 3} \quad -\mathbf{C}] \begin{bmatrix} \mathbf{X} \\ 1 \end{bmatrix}$$

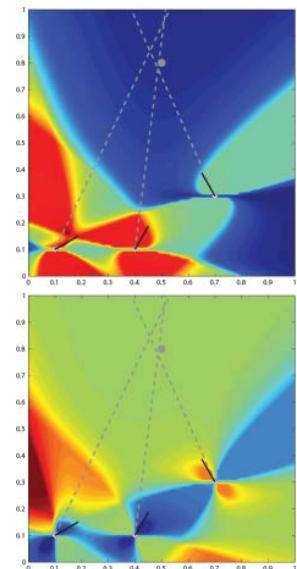


$$\underset{\mathbf{q}, \mathbf{C}, \mathbf{X}}{\text{minimize}} \left\| \begin{bmatrix} \tilde{x} \\ \tilde{y} \end{bmatrix} - \begin{bmatrix} u(\mathbf{R}(\mathbf{q}), \mathbf{C}, \mathbf{X}) / w(\mathbf{R}(\mathbf{q}), \mathbf{C}, \mathbf{X}) \\ v(\mathbf{R}(\mathbf{q}), \mathbf{C}, \mathbf{X}) / w(\mathbf{R}(\mathbf{q}), \mathbf{C}, \mathbf{X}) \end{bmatrix} \right\|^2 = \underset{\mathbf{q}, \mathbf{C}, \mathbf{X}}{\text{minimize}} \left\| \mathbf{b} - \mathbf{f}(\mathbf{R}(\mathbf{q}), \mathbf{C}, \mathbf{X}) \right\|^2$$

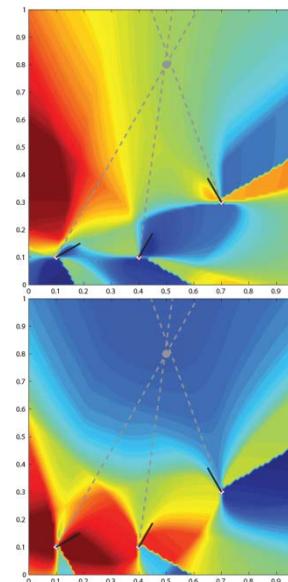
$$\mathbf{f}(\mathbf{R}(\mathbf{q}), \mathbf{C}, \mathbf{X}) = \begin{bmatrix} u/w \\ v/w \end{bmatrix}$$

$$\mathbf{J} = \begin{bmatrix} \frac{\partial \mathbf{f}(\mathbf{R}(\mathbf{q}), \mathbf{C}, \mathbf{X})}{\partial \mathbf{R}} & \frac{\partial \mathbf{R}}{\partial \mathbf{q}} \\ 2 \times 9 & 9 \times 4 \end{bmatrix} \quad \begin{bmatrix} \frac{\partial \mathbf{f}(\mathbf{R}(\mathbf{q}), \mathbf{C}, \mathbf{X})}{\partial \mathbf{C}} \\ 2 \times 3 \end{bmatrix} \quad \begin{bmatrix} \frac{\partial \mathbf{f}(\mathbf{R}(\mathbf{q}), \mathbf{C}, \mathbf{X})}{\partial \mathbf{X}} \\ 2 \times 3 \end{bmatrix}$$

$$\mathbf{J}^T \mathbf{J} \Delta \mathbf{x} = \mathbf{J}^T (\mathbf{b} - \mathbf{f}(\mathbf{x}))$$

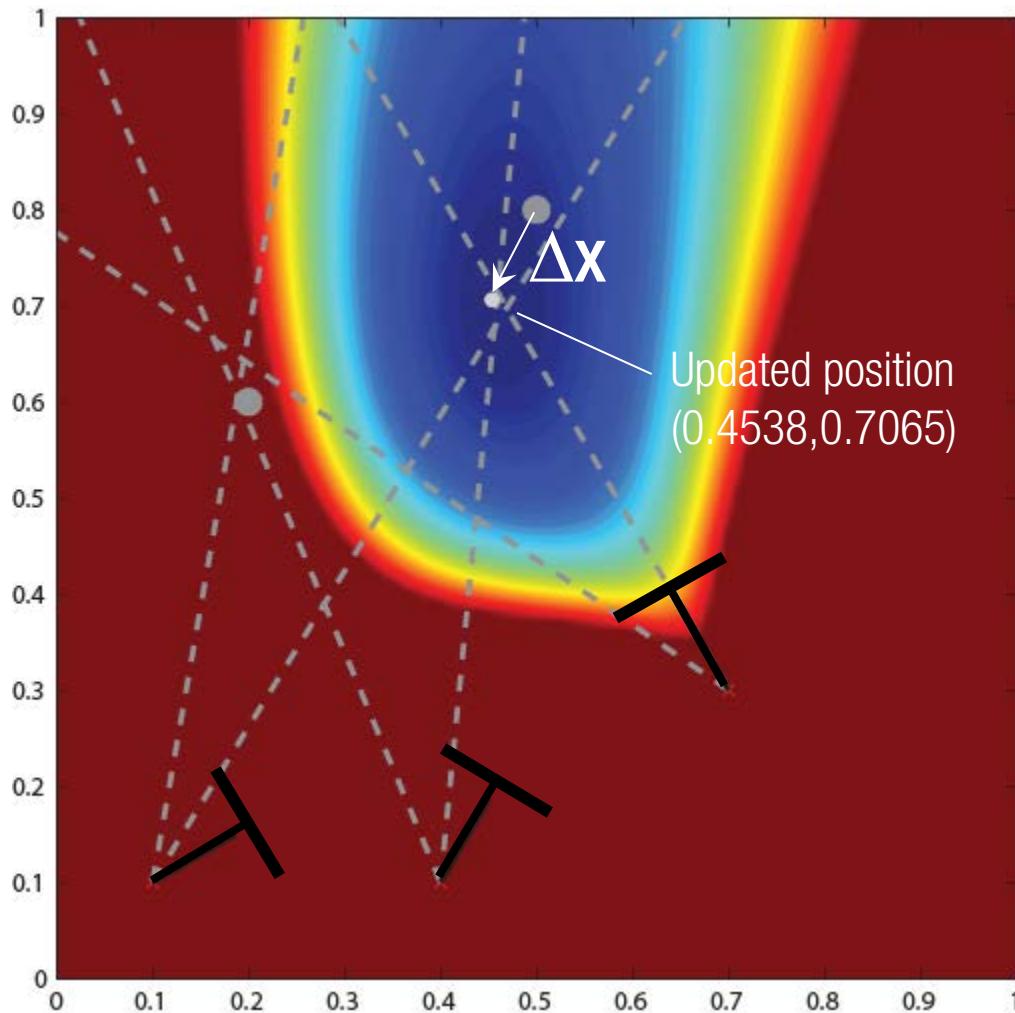


$$\Delta X + \Delta Y =$$



where  $\Delta \mathbf{x} = \begin{bmatrix} \Delta X \\ \Delta Y \end{bmatrix}$

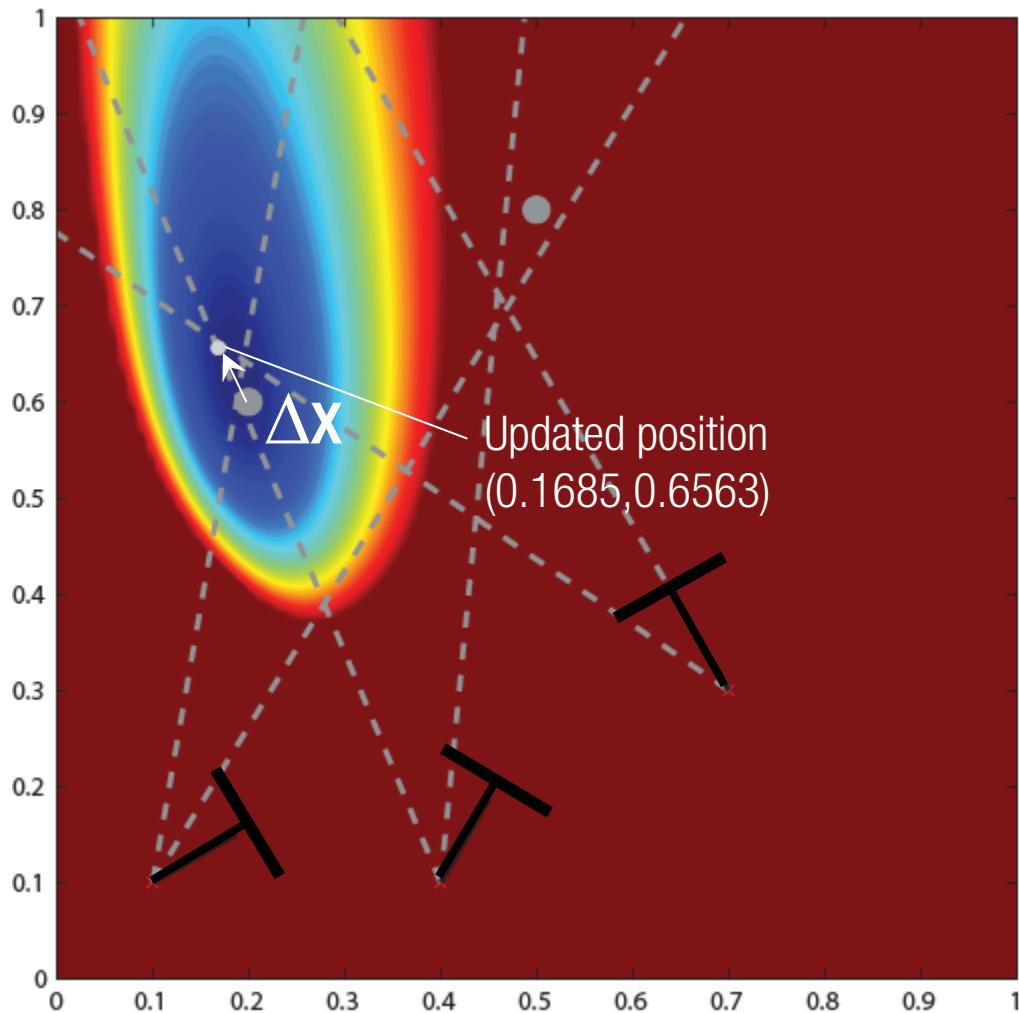
$$\Delta \mathbf{x} = (\mathbf{J}^\top \mathbf{J})^{-1} \mathbf{J}^\top (\mathbf{b} - \mathbf{f}(\mathbf{x}))$$



$$\begin{aligned}
 & \sum_{i=1}^3 \|\tilde{\mathbf{x}}_{i1} - f_{i1}(\mathbf{X})\|^2 \\
 &= \sum_{i=1}^3 \left\| \tilde{\mathbf{x}}_{i1} - U_{i1} / W_{i1} \right\|^2
 \end{aligned}$$

$\tilde{\mathbf{x}}_{i1}$   
 Camera index      Point index

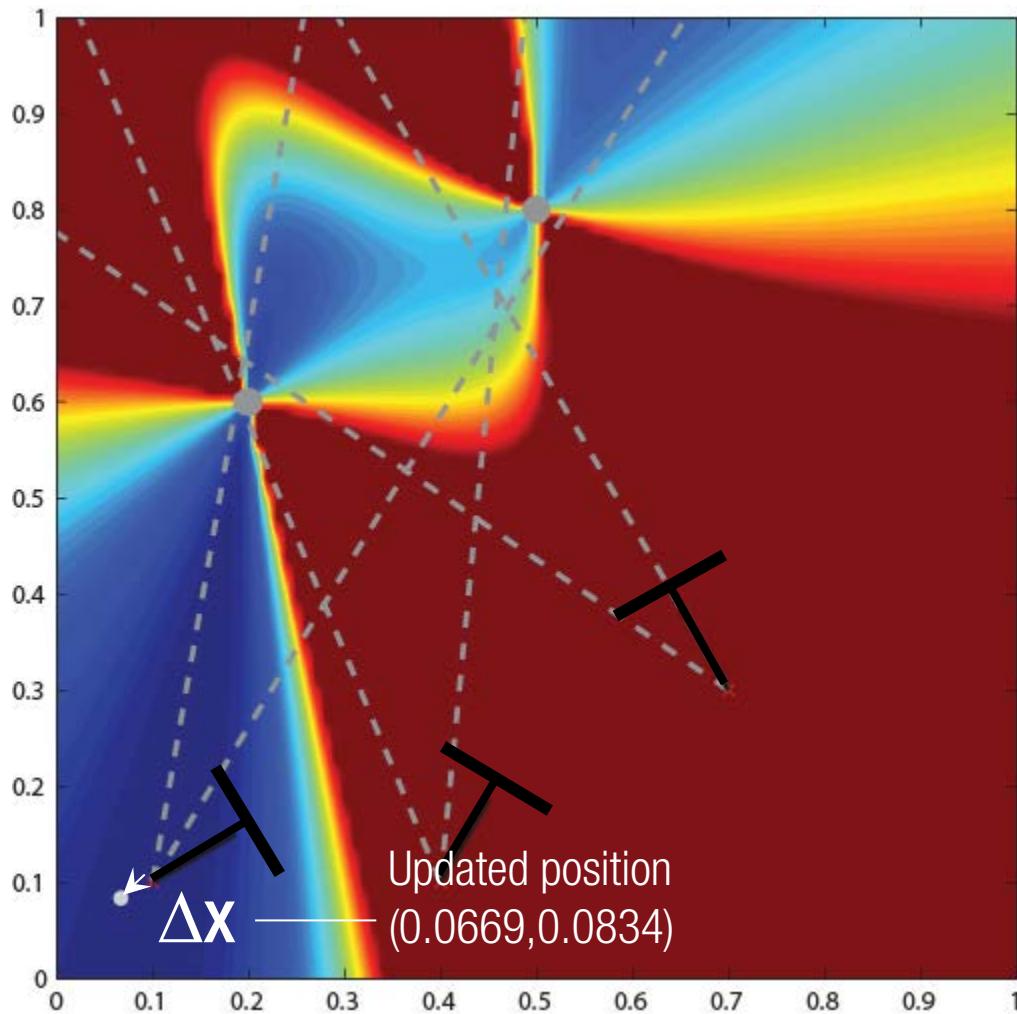
$$\Delta \mathbf{x} = (\mathbf{J}^\top \mathbf{J})^{-1} \mathbf{J}^\top (\mathbf{b} - \mathbf{f}(\mathbf{x}))$$



$$\begin{aligned}
 & \sum_{i=1}^3 \|\tilde{\mathbf{x}}_{i2} - \mathbf{f}_{i2}(\mathbf{X})\|^2 \\
 &= \sum_{i=1}^3 \left\| \tilde{\mathbf{x}}_{i2} - \frac{\mathbf{u}_{i2}}{w_{i2}} \right\|^2
 \end{aligned}$$

$\tilde{\mathbf{x}}_{i2}$   
 Camera index      Point index

$$\Delta \mathbf{x} = (\mathbf{J}^\top \mathbf{J})^{-1} \mathbf{J}^\top (\mathbf{b} - \mathbf{f}(\mathbf{x}))$$

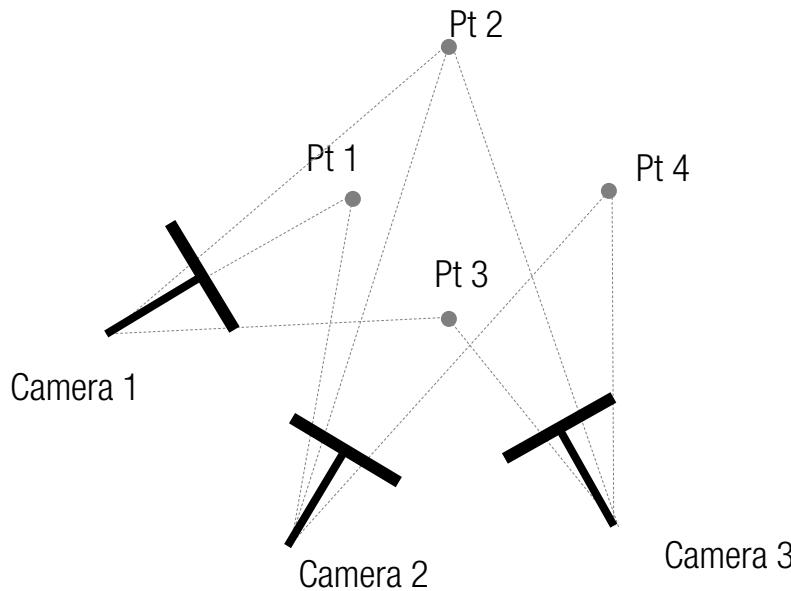


$$\sum_{j=1}^2 \left\| \tilde{\chi}_{1j} - f_{1j}(\mathbf{x}) \right\|^2 \\ = \sum_{j=1}^2 \left\| \tilde{\chi}_{1j} - U_{1j} / W_{1j} \right\|^2$$

$\tilde{\chi}_{1j}$   
Camera index      Point index

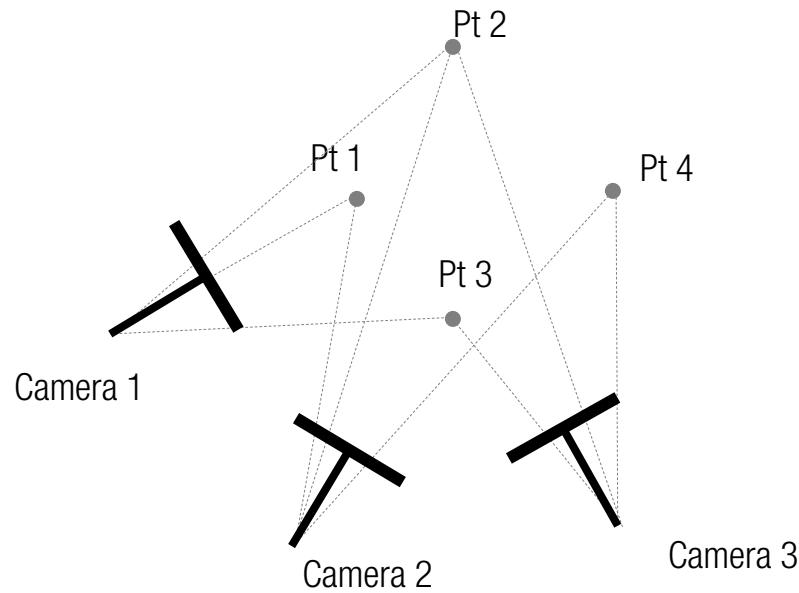
The figure consists of a 10x8 grid of colored rectangles. The columns are labeled at the top as Camera 1, Camera 2, Camera 3, Pt 1, Pt 2, Pt 3, and Pt 4. The rows are labeled on the left as J = 1 through J = 10. Each rectangle's color is determined by its row and column indices:

- Row J=1: (1,1) light orange, (1,2) orange, (1,3)-(1,7) grey, (1,8) grey
- Row J=2: (2,1)-(2,3) grey, (2,4) light orange, (2,5) orange, (2,6)-(2,8) grey
- Row J=3: (3,1)-(3,4) grey, (3,5)-(3,7) light blue, (3,8) grey
- Row J=4: (4,1)-(4,3) light orange, (4,4)-(4,6) grey, (4,7)-(4,8) grey
- Row J=5: (5,1)-(5,3) grey, (5,4)-(5,6) light orange, (5,7)-(5,8) grey
- Row J=6: (6,1)-(6,3) grey, (6,4)-(6,6) light orange, (6,7)-(6,8) grey
- Row J=7: (7,1)-(7,3) light orange, (7,4)-(7,6) grey, (7,7)-(7,8) grey
- Row J=8: (8,1)-(8,3) grey, (8,4)-(8,6) light orange, (8,7)-(8,8) grey
- Row J=9: (9,1)-(9,3) light orange, (9,4)-(9,6) grey, (9,7)-(9,8) grey
- Row J=10: (10,1)-(10,3) grey, (10,4)-(10,6) light orange, (10,7)-(10,8) blue

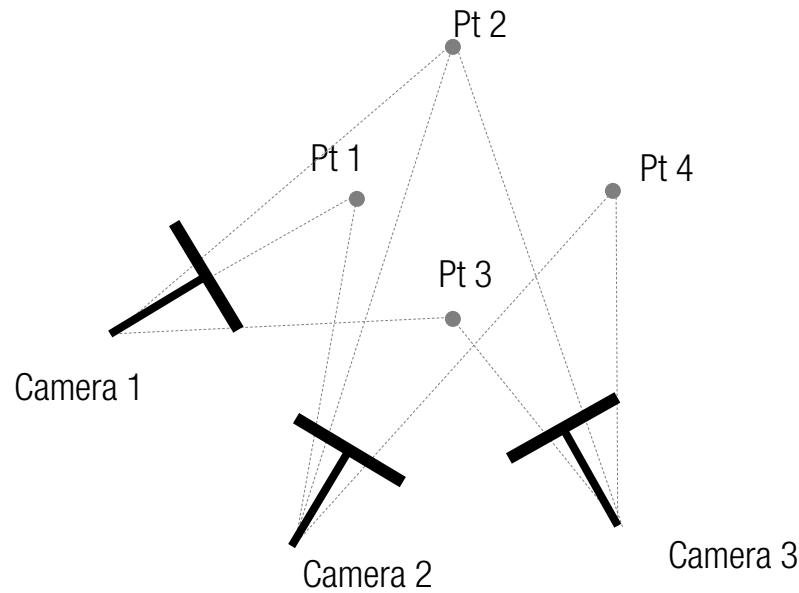
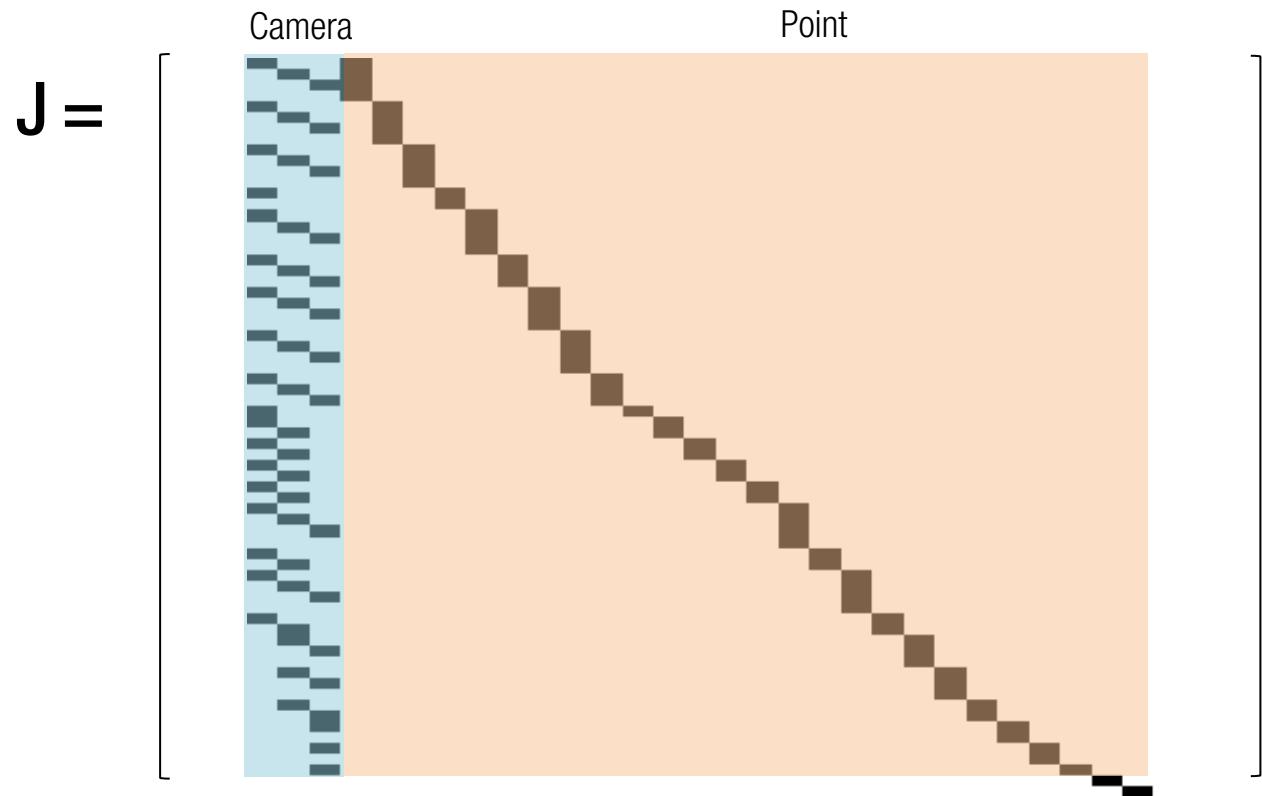


$$\Delta \mathbf{x} = \underbrace{(\mathbf{J}^\top \mathbf{J})^{-1}}_{\text{Main computational bottle neck}} \mathbf{J}^\top (\mathbf{b} - \mathbf{f}(\mathbf{x}))$$

$$\mathbf{J} = \left[ \begin{array}{c|cc|c} \text{Camera} & & & \text{Point} \\ \hline & \text{Row 1} & \text{Row 2} & \text{Row 1} \\ & \vdots & \vdots & \vdots \\ & \text{Row 8} & \text{Row 9} & \text{Row 8} \\ & \text{Row 10} & \text{Row 11} & \text{Row 9} \\ & \text{Row 12} & \text{Row 13} & \text{Row 10} \\ & \text{Row 14} & \text{Row 15} & \text{Row 11} \\ & \text{Row 16} & \text{Row 17} & \text{Row 12} \\ & \text{Row 18} & \text{Row 19} & \text{Row 13} \\ & \text{Row 20} & \text{Row 21} & \text{Row 14} \\ & \text{Row 22} & \text{Row 23} & \text{Row 15} \\ & \text{Row 24} & \text{Row 25} & \text{Row 16} \\ & \text{Row 26} & \text{Row 27} & \text{Row 17} \\ & \text{Row 28} & \text{Row 29} & \text{Row 18} \\ & \text{Row 30} & \text{Row 31} & \text{Row 19} \\ & \text{Row 32} & \text{Row 33} & \text{Row 20} \\ & \text{Row 34} & \text{Row 35} & \text{Row 21} \\ & \text{Row 36} & \text{Row 37} & \text{Row 22} \\ & \text{Row 38} & \text{Row 39} & \text{Row 23} \\ & \text{Row 40} & \text{Row 41} & \text{Row 24} \\ & \text{Row 42} & \text{Row 43} & \text{Row 25} \\ & \text{Row 44} & \text{Row 45} & \text{Row 26} \\ & \text{Row 46} & \text{Row 47} & \text{Row 27} \\ & \text{Row 48} & \text{Row 49} & \text{Row 28} \\ & \text{Row 50} & \text{Row 51} & \text{Row 29} \\ & \text{Row 52} & \text{Row 53} & \text{Row 30} \\ & \text{Row 54} & \text{Row 55} & \text{Row 31} \\ & \text{Row 56} & \text{Row 57} & \text{Row 32} \\ & \text{Row 58} & \text{Row 59} & \text{Row 33} \\ & \text{Row 60} & \text{Row 61} & \text{Row 34} \\ & \text{Row 62} & \text{Row 63} & \text{Row 35} \\ & \text{Row 64} & \text{Row 65} & \text{Row 36} \\ & \text{Row 66} & \text{Row 67} & \text{Row 37} \\ & \text{Row 68} & \text{Row 69} & \text{Row 38} \\ & \text{Row 70} & \text{Row 71} & \text{Row 39} \\ & \text{Row 72} & \text{Row 73} & \text{Row 40} \\ & \text{Row 74} & \text{Row 75} & \text{Row 41} \\ & \text{Row 76} & \text{Row 77} & \text{Row 42} \\ & \text{Row 78} & \text{Row 79} & \text{Row 43} \\ & \text{Row 80} & \text{Row 81} & \text{Row 44} \\ & \text{Row 82} & \text{Row 83} & \text{Row 45} \\ & \text{Row 84} & \text{Row 85} & \text{Row 46} \\ & \text{Row 86} & \text{Row 87} & \text{Row 47} \\ & \text{Row 88} & \text{Row 89} & \text{Row 48} \\ & \text{Row 90} & \text{Row 91} & \text{Row 49} \\ & \text{Row 92} & \text{Row 93} & \text{Row 50} \\ & \text{Row 94} & \text{Row 95} & \text{Row 51} \\ & \text{Row 96} & \text{Row 97} & \text{Row 52} \\ & \text{Row 98} & \text{Row 99} & \text{Row 53} \\ & \text{Row 100} & \text{Row 101} & \text{Row 54} \end{array} \right]$$

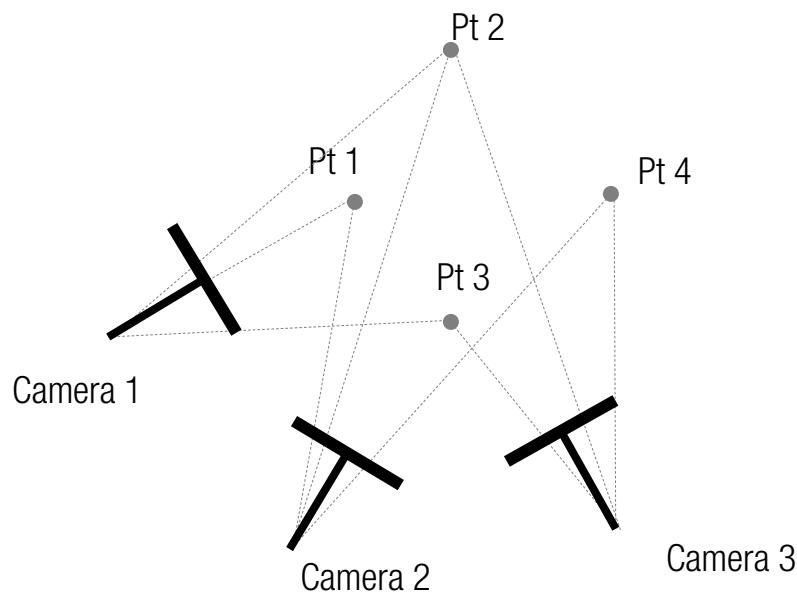


$$\Delta \mathbf{x} = \underbrace{\left( \mathbf{J}^T \mathbf{J} \right)^{-1}}_{\text{Main computational bottle neck}} \mathbf{J}^T (\mathbf{b} - \mathbf{f}(\mathbf{x}))$$



$$\Delta \mathbf{x} = \underbrace{(\mathbf{J}^\top \mathbf{J})^{-1}}_{\text{Main computational bottle neck}} \mathbf{J}^\top (\mathbf{b} - \mathbf{f}(\mathbf{x}))$$

$$J^T J = \begin{bmatrix} Camera \\ Camera \\ Point \end{bmatrix} \begin{bmatrix} Camera & Camera & Point \\ Camera & Camera & Point \\ Point & Point & Point \end{bmatrix}$$



$$\Delta \mathbf{x} = \underbrace{(\mathbf{J}^\top \mathbf{J})^{-1}}_{\text{Main computational bottle neck}} \mathbf{J}^\top (\mathbf{b} - \mathbf{f}(\mathbf{x}))$$

$$J^T J = \left[ \begin{array}{c|cc} A & \text{Camera} & \text{Point} \\ \hline \text{Camera} & \text{Camera} & \text{Point} \\ \text{Point} & \text{Point} & C \\ \hline B^T & B \end{array} \right]$$

$$\Delta x = \underbrace{(J^T J)^{-1} J^T (b - f(x))}_{\text{Main computational bottle neck}}$$

$$(A - BC^{-1}B^T) \Delta x_c = e_c - BC^{-1}e_p \quad : \text{Reduced system}$$

$$C \Delta x_p = e_p - B^T \Delta x_c \quad : \text{Back substitution}$$

**A****B**

$$\mathbf{B}^T \mathbf{J}^T \mathbf{J} =$$

**C**

$$(\mathbf{A} - \mathbf{B}\mathbf{C}^{-1}\mathbf{B}^T) \Delta \mathbf{x}_c = \mathbf{e}_c - \mathbf{B}\mathbf{C}^{-1}\mathbf{e}_p \quad : \text{Reduced system}$$

$$\mathbf{C} \Delta \mathbf{x}_p = \mathbf{e}_p - \mathbf{B}^T \Delta \mathbf{x}_c \quad : \text{Back substitution}$$

# 7. Bundle Adjustment



# 7. Bundle Adjustment







