# 3D Computer Vision

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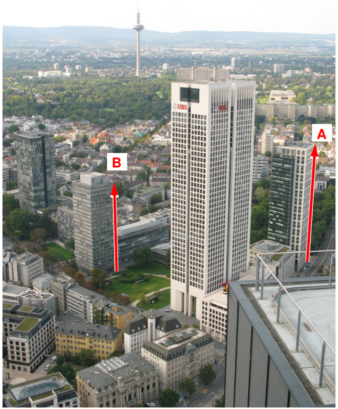
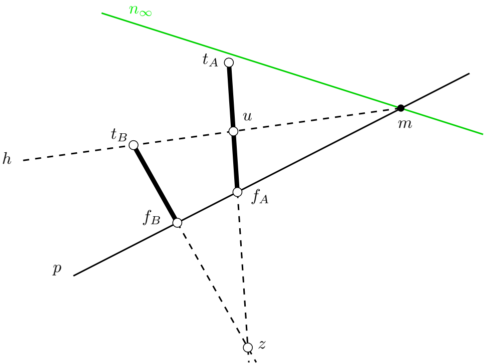
Open Informatics Master's Course

# Homework Problem

⊛ H2; 3pt: What is the ratio of heights of Building A to Building B?

- expected: conceptual solution; use notation from this figure
- deadline: LD+2 weeks

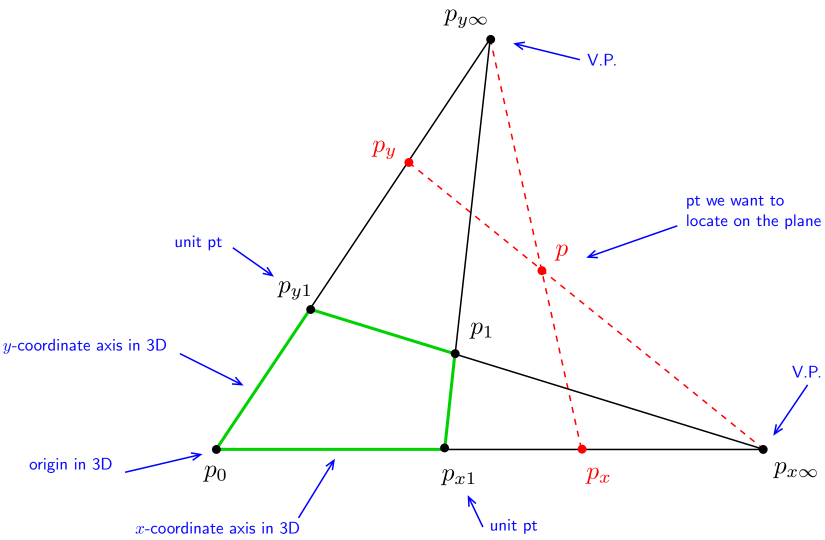



## Hints

1. What are the interesting properties of line $h$ connecting the top $t_B$ of Buiding B with the point $m$ at which the horizon intersects the line $p$ joining the foots $f_A$, $f_B$ of both buildings? [1 point]
2. How do we actually get the horizon $n_\infty$? (we do not see it directly, there are some hills there. . . ) [1 point]
3. Give a formula for measuring the length ratio. Make sure you distinguish points in 3D from their images. [formula = 1 point]

# 2D Projective Coordinates




$$[P_x] = [P_0\ P_{x1}\ P_x\ P_{x\infty}]$$

$$[P_y] = [P_0\ P_{y1}\ P_y\ P_{y\infty}]$$

# Application: Measuring on the Floor (Wall, etc)


San Giovanni in Laterano, Rome

- measuring distances on the floor in terms of tile units
- what are the dimensions of the seal? Is it circular (assuming square tiles)?
- needs no explicit camera calibration

because we can see the calibrating object (vanishing points)

# Module III

## Computing with a Single Camera



**covered by**

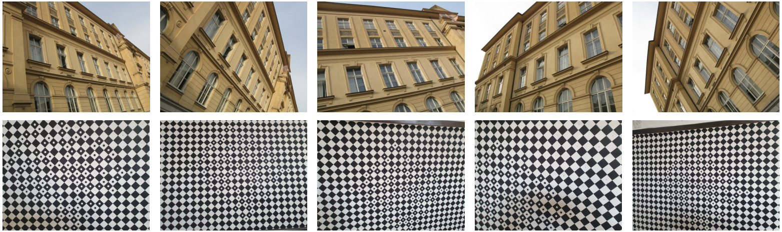
[1] [H&Z] Secs: 8.6, 7.1, 22.1

[2] Fischler, M.A. and Bolles, R.C . Random Sample Consensus: A Paradigm for Model Fitting with Applications to Image Analysis and Automated Cartography. *Communications of the ACM* 24(6):381–395, 1981

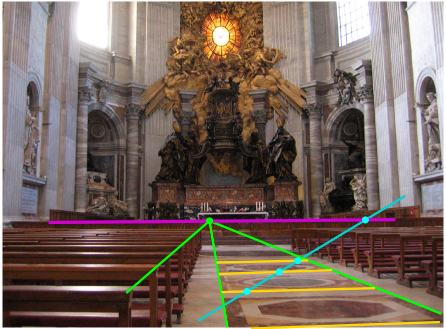
[3] [Golub & van Loan 2013, Sec. 2.5]

# Obtaining Vanishing Points and Lines

- orthogonal direction pairs can be collected from multiple images by camera rotation

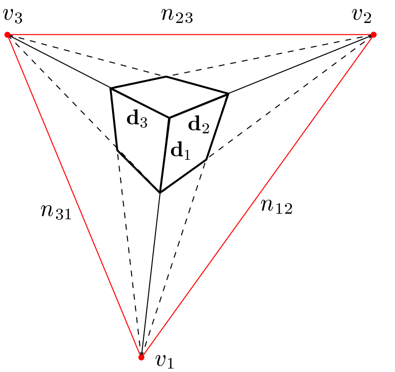


- vanishing line can be obtained from vanishing points and/or regularities (→49)



# ►Camera Calibration from Vanishing Points and Lines

**Problem:** Given finite vanishing points and/or vanishing lines, compute $\mathbf{K}$




$$\mathbf{d}_i = \lambda_i \mathbf{Q}^{-1} \underline{\mathbf{v}}_i, \qquad i = 1,2,3 \quad \rightarrow 43$$

$$\mathbf{p}_{ij} = \mu_{ij} \mathbf{Q}^\top \underline{\mathbf{n}}_{ij}, \quad i,j = 1,2,3,\ i \neq j \quad \rightarrow 39 \qquad (2)$$

- method: eliminate $\lambda_i$, $\mu_{ij}$, $\mathbf{R}$ from (2) and solve for $\mathbf{K}$.

**Configurations allowing elimination of $\mathbf{R}$**

1. orthogonal rays $\mathbf{d}_1 \perp \mathbf{d}_2$ in space then

$$0 = \mathbf{d}_1^\top \mathbf{d}_2 = \underline{\mathbf{v}}_1^\top \mathbf{Q}^{-\top} \mathbf{Q}^{-1} \underline{\mathbf{v}}_2 = \underline{\mathbf{v}}_1^\top \underbrace{(\mathbf{K}\mathbf{K}^\top)^{-1}}_{\boldsymbol{\omega} \text{ (IAC)}} \underline{\mathbf{v}}_2$$

2. orthogonal planes $\mathbf{p}_{ij} \perp \mathbf{p}_{ik}$ in space

$$0 = \mathbf{p}_{ij}^\top \mathbf{p}_{ik} = \underline{\mathbf{n}}_{ij}^\top \mathbf{Q}\mathbf{Q}^\top \underline{\mathbf{n}}_{ik} = \underline{\mathbf{n}}_{ij}^\top \boldsymbol{\omega}^{-1} \underline{\mathbf{n}}_{ik}$$

3. orthogonal ray and plane $\mathbf{d}_k \parallel \mathbf{p}_{ij}$, $k \neq i,j$ — normal parallel to optical ray

$$\mathbf{p}_{ij} \simeq \mathbf{d}_k \quad \Rightarrow \quad \mathbf{Q}^\top \underline{\mathbf{n}}_{ij} = \frac{\lambda_i}{\mu_{ij}} \mathbf{Q}^{-1} \underline{\mathbf{v}}_k \quad \Rightarrow \quad \underline{\mathbf{n}}_{ij} = \varkappa \mathbf{Q}^{-\top} \mathbf{Q}^{-1} \underline{\mathbf{v}}_k = \varkappa \boldsymbol{\omega} \underline{\mathbf{v}}_k, \quad \varkappa \neq 0$$

- $n_{ij}$ may be constructed from non-orthogonal $v_i$ and $v_j$, e.g. using the cross-ratio
- $\boldsymbol{\omega}$ is a symmetric, positive definite $3 \times 3$ matrix — IAC = Image of Absolute Conic
- equations are quadratic in $\mathbf{K}$ but linear in $\boldsymbol{\omega}$

# ►cont'd

| | configuration | equation | # constraints |
|---|---|---|---|
| (3) | orthogonal vanishing points | $\underline{\mathbf{v}}_i^\top \boldsymbol{\omega}\, \underline{\mathbf{v}}_j = 0$ | 1 |
| (4) | orthogonal vanishing lines | $\underline{\mathbf{n}}_{ij}^\top \boldsymbol{\omega}^{-1} \underline{\mathbf{n}}_{ik} = 0$ | 1 |
| (5) | vanishing points orthogonal to vanishing lines | $\underline{\mathbf{n}}_{ij} = \varkappa\, \boldsymbol{\omega}\, \underline{\mathbf{v}}_k$ | 2 |
| (6) | orthogonal image raster $\theta = \pi/2$ | $\omega_{12} = \omega_{21} = 0$ | 1 |
| (7) | unit aspect $a = 1$ when $\theta = \pi/2$ | $\omega_{11} - \omega_{22} = 0$ | 1 |
| (8) | known principal point $u_0 = v_0 = 0$ | $\omega_{13} = \omega_{31} = \omega_{23} = \omega_{32} = 0$ | 2 |

- these are homogeneous linear equations for the 5 parameters in $\boldsymbol{\omega}$ or $\boldsymbol{\omega}^{-1}$ in the form $\mathbf{D}\mathbf{w} = \mathbf{0}$

  $\varkappa$ can be eliminated from (5)
- we need at least 5 constraints for full $\boldsymbol{\omega}$ — symmetric $3 \times 3$
- we get $\mathbf{K}$ from $\boldsymbol{\omega}^{-1} = \mathbf{K}\mathbf{K}^\top$ by Choleski decomposition

  the decomposition returns a positive definite upper triangular matrix

  one avoids solving an explicit set of quadratic equations for the parameters in $\mathbf{K}$

Assuming orthogonal raster, unit aspect (ORUA): $\theta = \pi/2$, $a = 1$

$$\boldsymbol{\omega} \simeq \begin{bmatrix} 1 & 0 & -u_0 \\ 0 & 1 & -v_0 \\ -u_0 & -v_0 & f^2 + u_0^2 + v_0^2 \end{bmatrix}$$

**Ex 1:**

Assuming ORUA and known $m_0 = (u_0, v_0)$, two finite orthogonal vanishing points give $f$

$$\underline{\mathbf{v}}_1^\top \boldsymbol{\omega}\, \underline{\mathbf{v}}_2 = 0 \quad \Rightarrow \quad f^2 = \left| (\mathbf{v}_1 - \mathbf{m}_0)^\top (\mathbf{v}_2 - \mathbf{m}_0) \right|$$

in this formula, $\mathbf{v}_{1,2}$, $\mathbf{m}_0$ are Cartesian (not homogeneous)!

**Ex 2:**

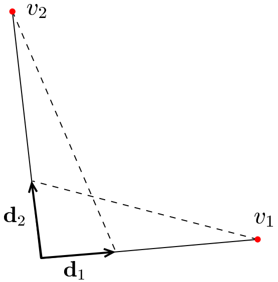
Non-orthogonal vanishing points $\mathbf{v}_i$, $\mathbf{v}_j$, known angle $\phi$: $\cos\phi = \dfrac{\underline{\mathbf{v}}_i^\top \boldsymbol{\omega} \underline{\mathbf{v}}_j}{\sqrt{\underline{\mathbf{v}}_i^\top \boldsymbol{\omega} \underline{\mathbf{v}}_i}\sqrt{\underline{\mathbf{v}}_j^\top \boldsymbol{\omega} \underline{\mathbf{v}}_j}}$

- leads to polynomial equations
- e.g. ORUA and $u_0 = v_0 = 0$ gives

$$(f^2 + \mathbf{v}_i^\top \mathbf{v}_j)^2 = (f^2 + \|\mathbf{v}_i\|^2) \cdot (f^2 + \|\mathbf{v}_j\|^2) \cdot \cos^2\phi$$

# ▶Camera Orientation from Two Finite Vanishing Points

**Problem:** Given $\mathbf{K}$ and two vanishing points corresponding to two known orthogonal directions $\mathbf{d}_1$, $\mathbf{d}_2$, compute camera orientation $\mathbf{R}$ with respect to the plane.




- 3D coordinate system choice, e.g.:

$$\mathbf{d}_1 = (1,0,0), \quad \mathbf{d}_2 = (0,1,0)$$

- we know that

$$\mathbf{d}_i \simeq \mathbf{Q}^{-1}\underline{\mathbf{v}}_i = (\mathbf{K}\mathbf{R})^{-1}\underline{\mathbf{v}}_i = \mathbf{R}^{-1}\underbrace{\mathbf{K}^{-1}\underline{\mathbf{v}}_i}_{\underline{\mathbf{w}}_i}$$

$$\mathbf{R}\mathbf{d}_i \simeq \underline{\mathbf{w}}_i$$

- knowing $\mathbf{d}_{1,2}$ we conclude that $\underline{\mathbf{w}}_i/\|\underline{\mathbf{w}}_i\|$ is the $i$-th column $\mathbf{r}_i$ of $\mathbf{R}$
- the third column is orthogonal: $\mathbf{r}_3 \simeq \mathbf{r}_1 \times \mathbf{r}_2$

$$\mathbf{R} = \begin{bmatrix} \frac{\underline{\mathbf{w}}_1}{\|\underline{\mathbf{w}}_1\|} & \frac{\underline{\mathbf{w}}_2}{\|\underline{\mathbf{w}}_2\|} & \frac{\underline{\mathbf{w}}_1 \times \underline{\mathbf{w}}_2}{\|\underline{\mathbf{w}}_1 \times \underline{\mathbf{w}}_2\|} \end{bmatrix}$$

- we have to care about the signs $\pm\underline{\mathbf{w}}_i$ (such that $\det \mathbf{R} = 1$)

some suitable scenes

# Application: Planar Rectification

**Principle:** Rotate camera (image plane) parallel to the plane of interest.

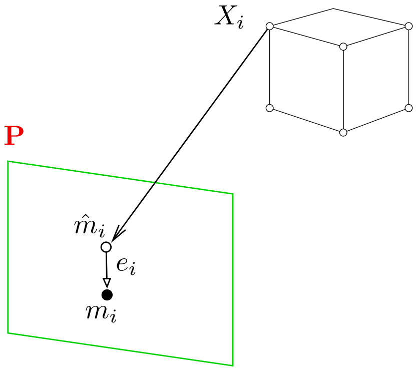
$$\underline{\mathbf{m}} \simeq \mathbf{K}\mathbf{R}\begin{bmatrix}\mathbf{I} & -\mathbf{C}\end{bmatrix}\underline{\mathbf{X}} \qquad \underline{\mathbf{m}}' \simeq \mathbf{K}\begin{bmatrix}\mathbf{I} & -\mathbf{C}\end{bmatrix}\underline{\mathbf{X}}$$

$$\underline{\mathbf{m}}' \simeq \mathbf{K}(\mathbf{K}\mathbf{R})^{-1}\,\underline{\mathbf{m}} = \mathbf{K}\mathbf{R}^{\top}\mathbf{K}^{-1}\,\underline{\mathbf{m}} = \mathbf{H}\,\underline{\mathbf{m}}$$

- $\mathbf{H}$ is the rectifying homography
- both $\mathbf{K}$ and $\mathbf{R}$ can be calibrated from two finite vanishing points — assuming ORUA →57
- not possible when one of them is (or both are) infinite
- without ORUA we would need 4 additional views to calibrate $\mathbf{K}$ as on →54

# ►Camera Resection

Camera calibration and orientation from a known set of $k \geq 6$ reference points and their images $\{(X_i, m_i)\}_{i=1}^{6}$.

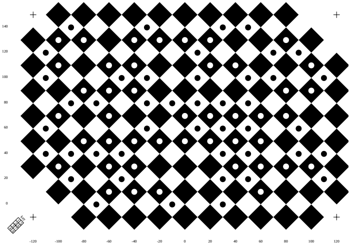



- $X_i$ are considered exact
- $m_i$ is a measurement subject to detection error

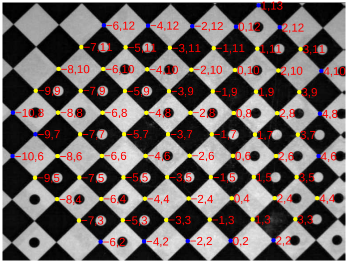
$$\mathbf{m}_i = \hat{\mathbf{m}}_i + \mathbf{e}_i \qquad \text{Cartesian}$$

- where $\lambda_i \, \underline{\hat{\mathbf{m}}}_i = \mathbf{P}\underline{\mathbf{X}}_i$

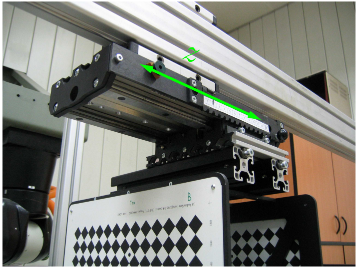
# Resection Targets




calibration chart




automatic calibration point detection
based on a distributed bitcode ($2 \times 4 = 8$ bits)




resection target with translation stage

- target translated at least once
- by a calibrated (known) translation
- $X_i$ point locations looked up in a table based on their bitcode

# ▶The Minimal Problem for Camera Resection

**Problem:** Given $k = 6$ corresponding pairs $\{(X_i, m_i)\}_{i=1}^{k}$, find $\mathbf{P}$

$$\lambda_i \underline{\mathbf{m}}_i = \mathbf{P}\underline{\mathbf{X}}_i, \qquad \mathbf{P} = \begin{bmatrix} \mathbf{q}_1^\top & q_{14} \\ \mathbf{q}_2^\top & q_{24} \\ \mathbf{q}_3^\top & q_{34} \end{bmatrix}$$

$$\underline{\mathbf{X}}_i = (x_i, y_i, z_i, 1), \quad i = 1, 2, \ldots, k, \; k = 6$$
$$\underline{\mathbf{m}}_i = (u_i, v_i, 1), \quad \lambda_i \in \mathbb{R}, \; \lambda_i \neq 0, \; |\lambda_i| < \infty$$

easily modifiable for infinite points $X_i$ but be aware of →64

expanded: $\lambda_i u_i = \mathbf{q}_1^\top \mathbf{X}_i + q_{14}, \quad \lambda_i v_i = \mathbf{q}_2^\top \mathbf{X}_i + q_{24}, \quad \lambda_i = \mathbf{q}_3^\top \mathbf{X}_i + q_{34}$

after elimination of $\lambda_i$: $(\mathbf{q}_3^\top \mathbf{X}_i + q_{34}) u_i = \mathbf{q}_1^\top \mathbf{X}_i + q_{14}, \quad (\mathbf{q}_3^\top \mathbf{X}_i + q_{34}) v_i = \mathbf{q}_2^\top \mathbf{X}_i + q_{24}$

**Then**

$$\mathbf{A}\,\mathbf{q} = \begin{bmatrix} \mathbf{X}_1^\top & 1 & \mathbf{0}^\top & 0 & -u_1\mathbf{X}_1^\top & -u_1 \\ \mathbf{0}^\top & 0 & \mathbf{X}_1^\top & 1 & -v_1\mathbf{X}_1^\top & -v_1 \\ \vdots & & & & & \vdots \\ \mathbf{X}_k^\top & 1 & \mathbf{0}^\top & 0 & -u_k\mathbf{X}_k^\top & -u_k \\ \mathbf{0}^\top & 0 & \mathbf{X}_k^\top & 1 & -v_k\mathbf{X}_k^\top & -v_k \end{bmatrix} \cdot \begin{bmatrix} \mathbf{q}_1 \\ q_{14} \\ \mathbf{q}_2 \\ q_{24} \\ \mathbf{q}_3 \\ q_{34} \end{bmatrix} = \mathbf{0} \qquad (9)$$

- we need 11 indepedent parameters for $\mathbf{P}$
- $\mathbf{A} \in \mathbb{R}^{2k,12}, \quad \mathbf{q} \in \mathbb{R}^{12}$
- 6 points in a general position give $\operatorname{rank} \mathbf{A} = 12$ and there is no (non-trivial) null space
- drop one row to get rank-11 matrix, then the basis vector of the null space of $\mathbf{A}$ gives $\mathbf{q}$

# ▶The Jack-Knife Solution for $k = 6$

- given the 6 correspondences, we have 12 equations for the 11 parameters
- can we use all the information present in the 6 points?

## Jack-knife estimation

1. $n := 0$
2. for $i = 1, 2, \ldots, 2k$ do
   a) delete $i$-th row from $\mathbf{A}$, this gives $\mathbf{A}_i$
   b) if $\dim \operatorname{null} \mathbf{A}_i > 1$ continue with the next $i$
   c) $n := n + 1$
   d) compute the right null-space $\mathbf{q}_i$ of $\mathbf{A}_i$ — e.g. by 'economy-size' SVD
   e) $\hat{\mathbf{q}}_i := \mathbf{q}_i$ normalized to $q_{34} = 1$ and dimension-reduced — assuming finite cam. with $P_{3,4} = 1$
3. from all $n$ vectors $\hat{\mathbf{q}}_i$ collected in Step 2.e compute

$$\mathbf{q} = \frac{1}{n}\sum_{i=1}^{n}\hat{\mathbf{q}}_i, \qquad \operatorname{var}[\mathbf{q}] = \frac{n-1}{n}\operatorname{diag}\sum_{i=1}^{n}(\hat{\mathbf{q}}_i - \mathbf{q})(\hat{\mathbf{q}}_i - \mathbf{q})^\top$$

regular for $n \geq 11$
variance of the sample mean

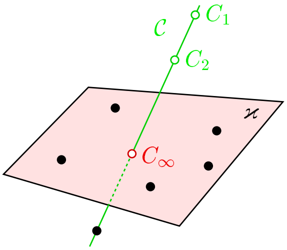
- have a solution + an error estimate, per individual elements of $\mathbf{P}$ (except $P_{34}$)
- at least 5 points must be in a general position (→64)
- large error indicates near degeneracy
- computation not efficient with $k > 6$ points, needs $\binom{2k}{11}$ draws, e.g. $k = 7 \Rightarrow 364$ draws
- better error estimation method: decompose $\mathbf{P}_i$ to $\mathbf{K}_i$, $\mathbf{R}_i$, $\mathbf{t}_i$ (→33), represent $\mathbf{R}_i$ with 3 parameters (e.g. Euler angles, or in exponential map representation →144) and compute the errors for the parameters
- even better: use the $\mathrm{SE}(3)$ Lie group for $(\mathbf{R}_i, \mathbf{t}_i)$ and average its Lie-algebraic representations

# ▶Degenerate (Critical) Configurations for Camera Resection

Let $\mathcal{X} = \{X_i;\ i = 1, \dots\}$ be a set of points and $\mathbf{P}_1 \not\simeq \mathbf{P}_j$ be two regular (rank-3) cameras. Then two configurations $(\mathbf{P}_1, \mathcal{X})$ and $(\mathbf{P}_j, \mathcal{X})$ are image-equivalent if

$$\mathbf{P}_1 \underline{\mathbf{X}}_i \simeq \mathbf{P}_j \underline{\mathbf{X}}_i \quad \text{for all} \quad X_i \in \mathcal{X}$$

there is a non-trivial set of other cameras that see the same image



Case 4

**Results**

- importantly: If all calibration points $X_i \in \mathcal{X}$ lie on a plane $\varkappa$ then camera resection is non-unique and all image-equivalent camera centers lie on a spatial line $\mathcal{C}$ with the $C_\infty = \varkappa \cap \mathcal{C}$ excluded

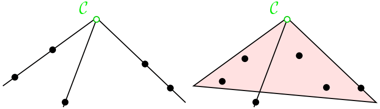
  this also means we cannot resect if all $X_i$ are infinite
- and more: by adding points $X_i \in \mathcal{X}$ to $\mathcal{C}$ we gain nothing
- there are additional image-equivalent configurations, see next

Proof sketch: If $\mathbf{Q}$, $\mathbf{T}$ are suitable homographies then $\mathbf{P}_1 \simeq \mathbf{Q}\mathbf{P}_0\mathbf{T}$, where $\mathbf{P}_0$ is canonical and the analysis can be made with $\hat{\mathbf{P}}_j \simeq \mathbf{Q}^{-1}\mathbf{P}_j$

$$\mathbf{P}_0 \underbrace{\mathbf{T}\underline{\mathbf{X}}_i}_{\underline{\mathbf{Y}}_i} \simeq \hat{\mathbf{P}}_j \underbrace{\mathbf{T}\underline{\mathbf{X}}_i}_{\underline{\mathbf{Y}}_i} \quad \text{for all} \quad Y_i \in \mathcal{Y}$$

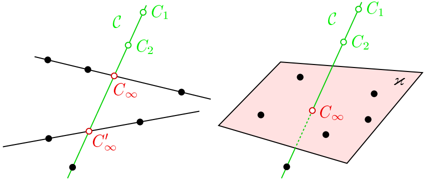
see [H&Z, Sec. 22.1.2] for a full prof

# cont'd (all cases)




Case 5 Case 6

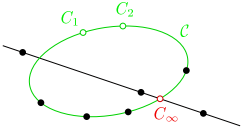
- points lie on three optical rays or one optical plane and one optical plane
- cameras $C_1$, $C_2$ co-located at point $\mathcal{C}$
- Case 5: camera sees 3 isolated point images
- Case 6: cam. sees a line of points and an isolated point




Case 3 **Case 4**

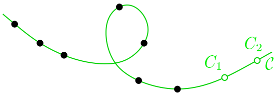
- points lie on a <u>line</u> $\mathcal{C}$ and
  1. on two lines meeting $\mathcal{C}$ at $C_\infty$, $C'_\infty$
  2. or on a plane meeting $\mathcal{C}$ at $C_\infty$
- cameras lie on a line $\mathcal{C} \setminus \{C_\infty, C'_\infty\}$
- Case 3: camera sees 2 lines of points
- Case 4: **dangerous!**

Case 2




- points lie on a <u>planar conic</u> $\mathcal{C}$ and an additional line meeting $\mathcal{C}$ at $C_\infty$
- cameras lie on $\mathcal{C} \setminus \{C_\infty\}$ not necessarily an ellipse
- Case 2: camera sees 2 lines of points

Case 1




- points and cameras all lie on a <u>twisted cubic</u> $\mathcal{C}$
- Case 1: camera sees points on a conic

  dangerous but unlikely to occur

# ▶Three-Point Exterior Orientation Problem (P3P)

Calibrated camera rotation and translation from Perspective images of 3 reference Points.

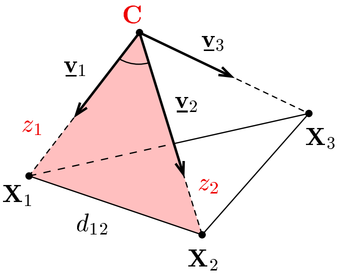
**Problem:** Given $\mathbf{K}$ and three corresponding pairs $\{(m_i, X_i)\}_{i=1}^{3}$, find $\mathbf{R}$, $\mathbf{C}$ by solving

$$\lambda_i \underline{\mathbf{m}}_i = \mathbf{K}\mathbf{R}\,(\mathbf{X}_i - \mathbf{C}), \qquad i = 1, 2, 3 \qquad\qquad \mathbf{X}_i \text{ Cartesian}$$

1. Transform $\underline{\mathbf{v}}_i \stackrel{\text{def}}{=} \mathbf{K}^{-1}\underline{\mathbf{m}}_i$. Then

$$\lambda_i \underline{\mathbf{v}}_i = \mathbf{R}\,(\mathbf{X}_i - \mathbf{C}). \tag{10}$$

2. If there was no rotation in (10), the situation would look like this




3. and we could shoot 3 lines from the given points $\mathbf{X}_i$ in given directions $\underline{\mathbf{v}}_i$ to get $\mathbf{C}$
4. given $\mathbf{C}$ we solve (10) for $\lambda_i$, $\mathbf{R}$

# ►P3P cont'd

## If there is rotation $\mathbf{R}$

1. Eliminate $\mathbf{R}$ by taking — rotation preserves length: $\|\mathbf{R}\mathbf{x}\| = \|\mathbf{x}\|$

$$|\lambda_i| \cdot \|\underline{\mathbf{v}}_i\| = \|\mathbf{X}_i - \mathbf{C}\| \stackrel{\text{def}}{=} z_i \qquad (11)$$

2. Consider only angles among $\underline{\mathbf{v}}_i$ and apply Cosine Law per triangle $(\mathbf{C}, \mathbf{X}_i, \mathbf{X}_j)$ $i, j = 1, 2, 3,\ i \neq j$

$$d_{ij}^2 = z_i^2 + z_j^2 - 2\, z_i\, z_j\, c_{ij},$$

$$z_i = \|\mathbf{X}_i - \mathbf{C}\|,\ \ d_{ij} = \|\mathbf{X}_j - \mathbf{X}_i\|,\ \ c_{ij} = \cos(\angle \underline{\mathbf{v}}_i\, \underline{\mathbf{v}}_j)$$

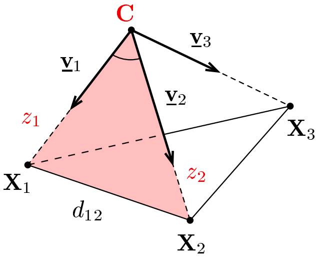
4. Solve the system of 3 quadratic eqs in 3 unknowns $z_i$ — [Fischler & Bolles, 1981]

   there may be no real root

   there are up to 4 solutions that cannot be ignored (verify on additional points)

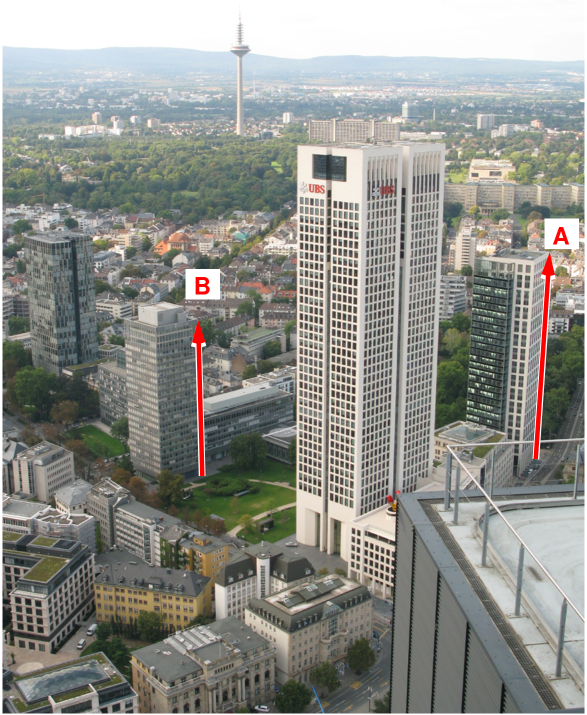
5. Compute $\mathbf{C}$ by trilateration (3-sphere intersection) from $\mathbf{X}_i$ and $z_i$; then $\lambda_i$ from (11)

6. Compute $\mathbf{R}$ from (10) — we will solve this problem next →70




Similar problems (P4P with unknown $f$) at http://aag.ciirc.cvut.cz/minimal/ (papers, code)

Thank You


A
B
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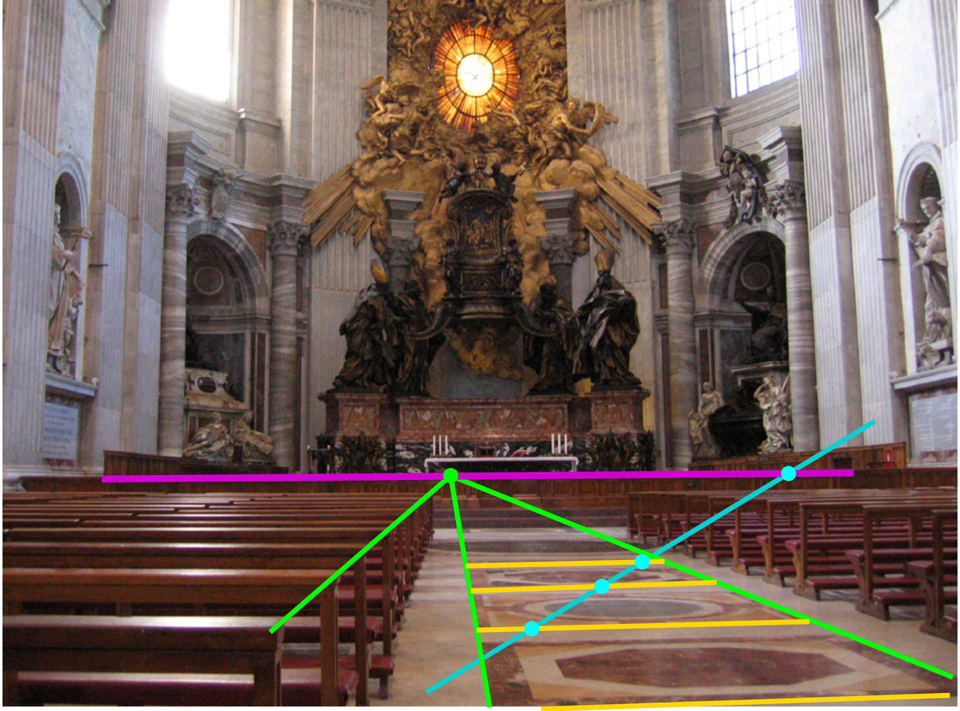


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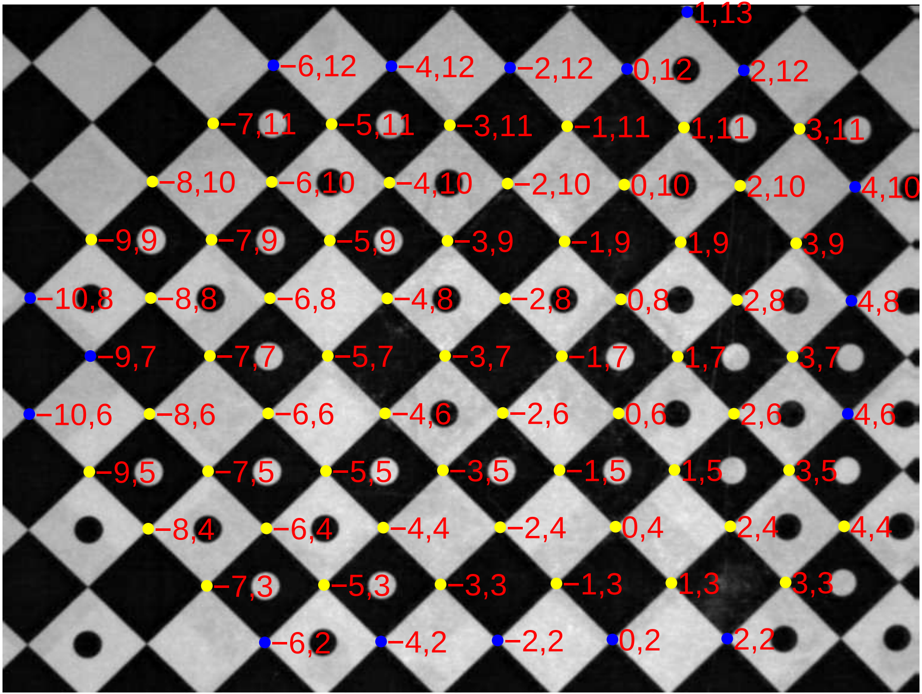
FILMS
TICKETS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