COMPUTER VISION AND PHOTOGRAMMETRY

SELF-CALIBRATION

TODAY

- so far…

- Geometrical definitions
- Self-Calibration

SUMMARY

3D MODELLING FROM IMAGES PIPELINE

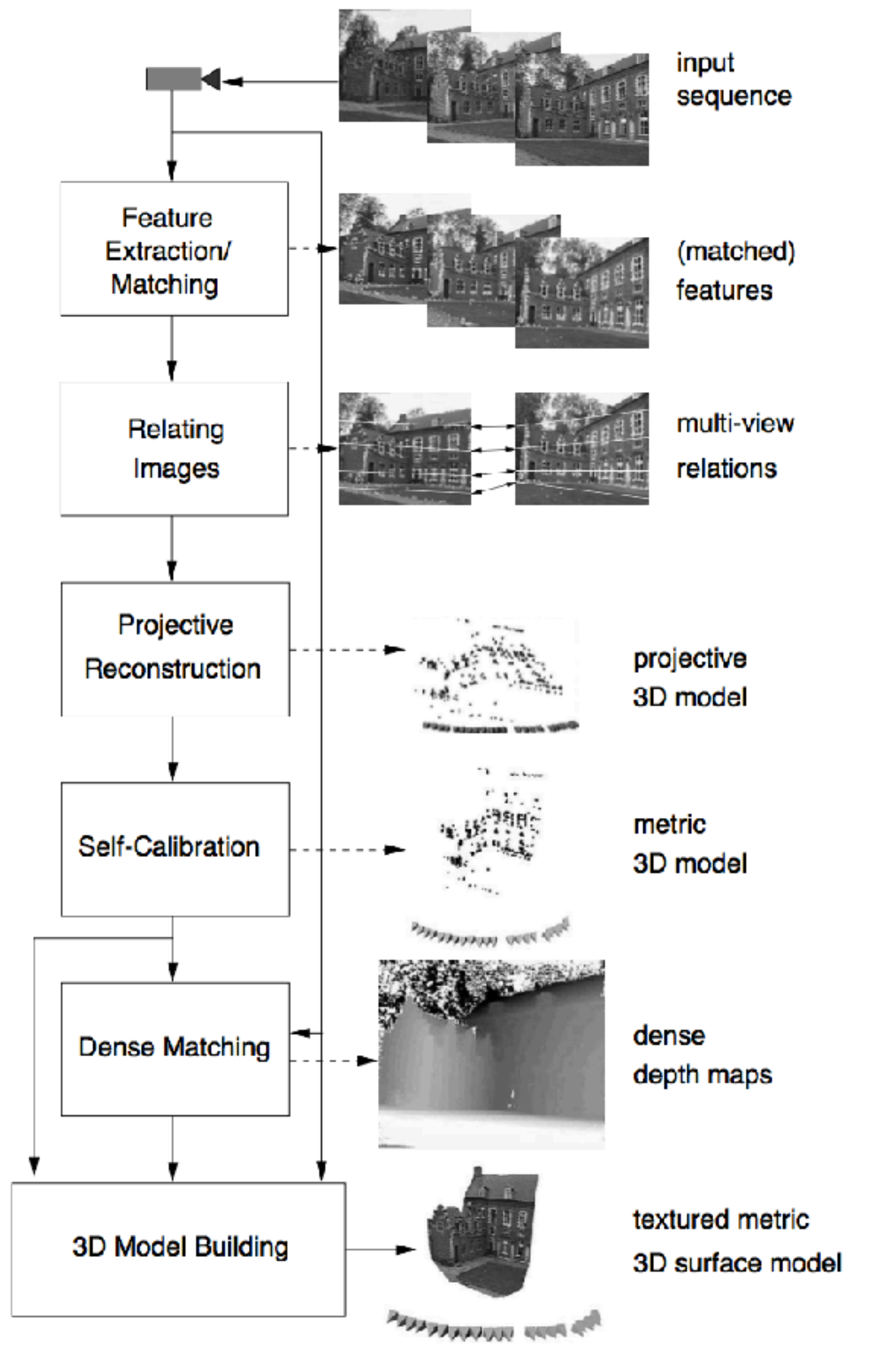


Figure 1.7: Overview of the presented approach for 3D modeling from images

KEYPOINT DETECTORS

- Harris Corners
- DoG
- LoG
- Scale and orientation

FEATURE DESCRIPTOR

- Invariant to illumination
- Invariant to rotation
- Invariant (somehow) to viewing angle

MATCHING

- Nearest Neighbour Distance Ratio
- RANSAC
  - Evaluate a (random) hypothesis to reject outliers

RELATING IMAGES

- Fundamental Matrix (more views?)
- Projection Matrices
- Triangulation
  - PROJECTIVE RECONSTRUCTION
- if K (calibrated) Essential Matrix
  - METRIC RECONSTRUCTION
- IF NOT?? Self-calibration (TODAY)

DENSE MATCHING

- Stereo Matching
- Rectification
- SSD, NCC

3D MODELING

- From 3D points to triangles
- Texturing
- Other material properties??

PROJECTIVE GEOMETRY

HOMOGENEOUS COORDINATES

Homogeneous representation of lines

$ax + by + c = 0 \qquad (a,b,c)^{\mathsf{T}}$

$(ka)x + (kb)y + kc = 0, \forall k \neq 0 \qquad (a,b,c)^{\mathsf{T}} \sim k(a,b,c)^{\mathsf{T}}$

equivalence class of vectors, any vector is representative

Set of all equivalence classes in $\mathbf{R}^3 - (0,0,0)^{\mathsf{T}}$ forms $\mathbf{P}^2$

Homogeneous representation of points

$\mathrm{x} = (x,y)^{\mathsf{T}}$ on $\mathrm{l} = (a,b,c)^{\mathsf{T}}$ if and only if $ax + by + c = 0$

$(x,y,1)(a,b,c)^{\mathsf{T}} = (x,y,1)\mathrm{l} = 0 \qquad (x,y,1)^{\mathsf{T}} \sim k(x,y,1)^{\mathsf{T}}, \forall k \neq 0$

The point x lies on the line l if and only if $\mathrm{x}^{\mathsf{T}}\mathrm{l} = \mathrm{l}^{\mathsf{T}}\mathrm{x} = 0$

Homogeneous coordinates $(x_1, x_2, x_3)^{\mathsf{T}}$ but only 2DOF

Inhomogeneous coordinates $(x, y)^{\mathsf{T}}$

POINTS FROM LINES AND VICE-VERSA

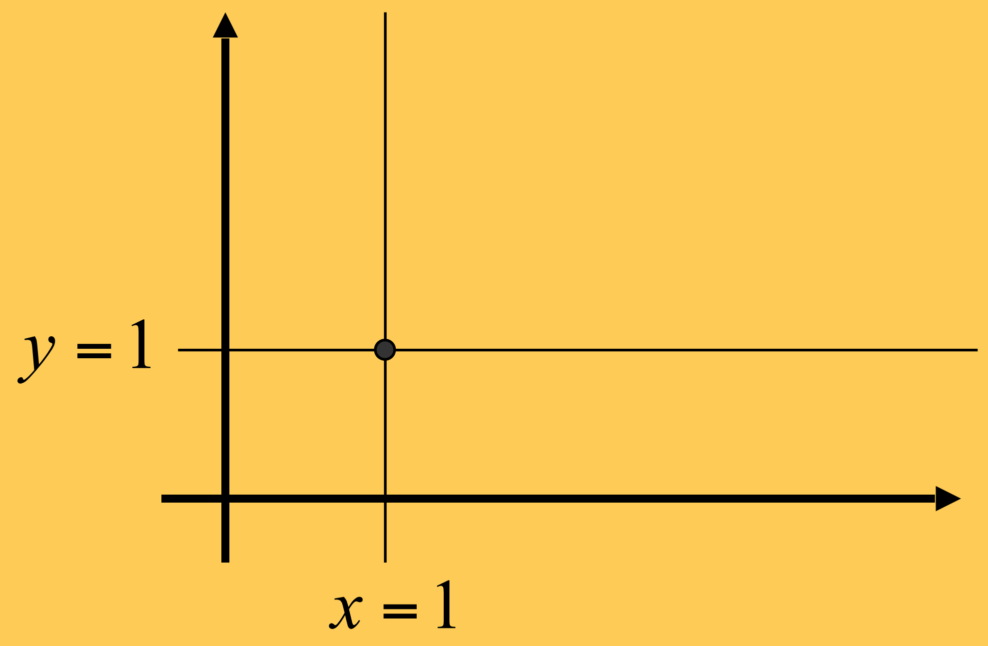
Intersections of lines

The intersection of two lines $\mathbf{l}$ and $\mathbf{l}'$ is $\mathbf{x} = \mathbf{l} \times \mathbf{l}'$

Line joining two points

The line through two points $\mathbf{x}$ and $\mathbf{x}'$ is $\mathbf{l} = \mathbf{x} \times \mathbf{x}'$

Example

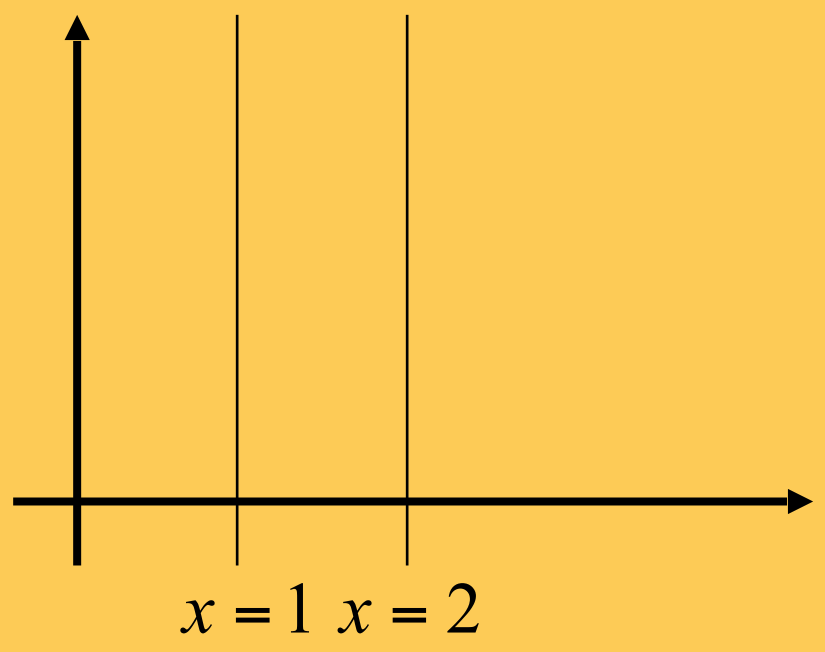


IDEAL POINTS AND THE LINE AT INFINITY

Intersections of parallel lines

$\mathbf{l} = (a, b, c)^\mathsf{T}$ and $\mathbf{l}' = (a, b, c')^\mathsf{T}$ $\qquad \mathbf{l} \times \mathbf{l}' = (b, -a, 0)^\mathsf{T}$

Example



$(b, -a)$ tangent vector

(a, b) normal direction

Ideal points $\quad (x_1, x_2, 0)^\mathsf{T}$

Line at infinity $\quad \mathbf{l}_\infty = (0, 0, 1)^\mathsf{T}$

$\mathbf{P}^2 = \mathbf{R}^2 \cup \mathbf{l}_\infty$

Note that in $\mathbf{P}^2$ there is no distinction between ideal points and others

DUALITY

$$\mathbf{x} \longleftrightarrow \mathbf{l}$$

$$\mathbf{x}^{T}\mathbf{l} = 0 \longleftrightarrow \mathbf{l}^{T}\mathbf{x} = 0$$

$$\mathbf{x} = \mathbf{l} \times \mathbf{l}' \longleftrightarrow \mathbf{l} = \mathbf{x} \times \mathbf{x}'$$

Duality principle:

To any theorem of 2-dimensional projective geometry there corresponds a dual theorem, which may be derived by interchanging the role of points and lines in the original theorem

CONICS

Curve described by 2nd-degree equation in the plane

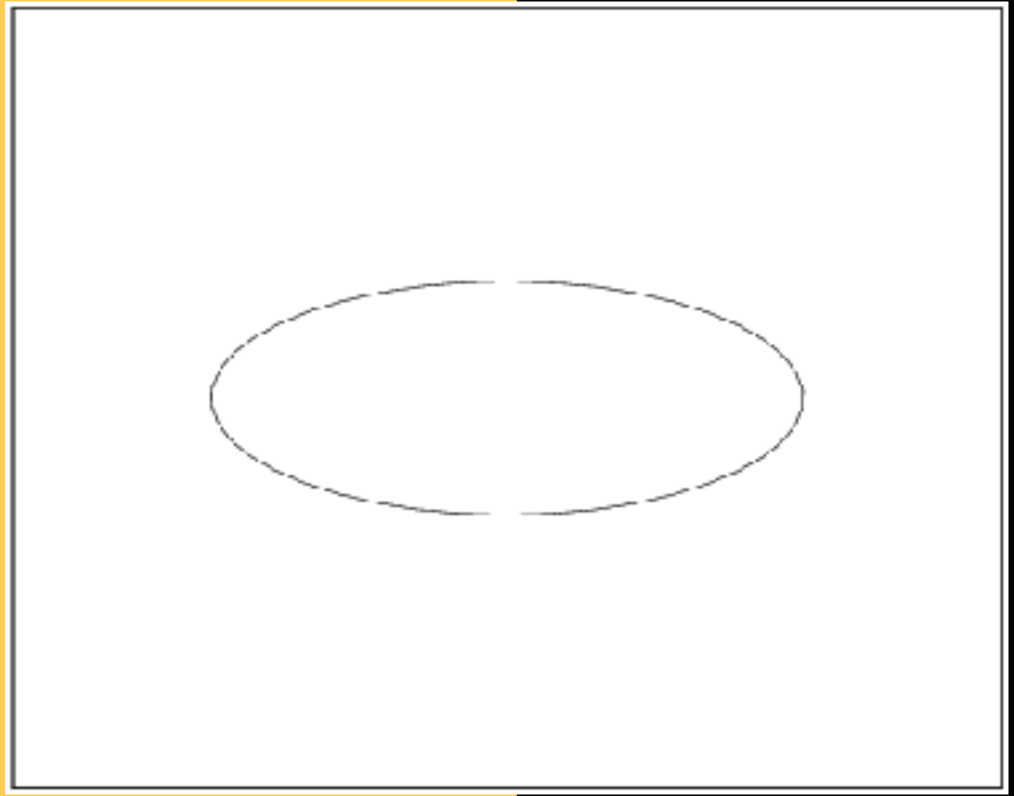
$$ax^2 + bxy + cy^2 + dx + ey + f = 0$$

or *homogenized* $x \boxed{?} x_1/x_3,\ y \boxed{?} x_2/x_3$

$$ax_1^2 + bx_1x_2 + cx_2^2 + dx_1x_3 + ex_2x_3 + fx_3^2 = 0$$

or in matrix form

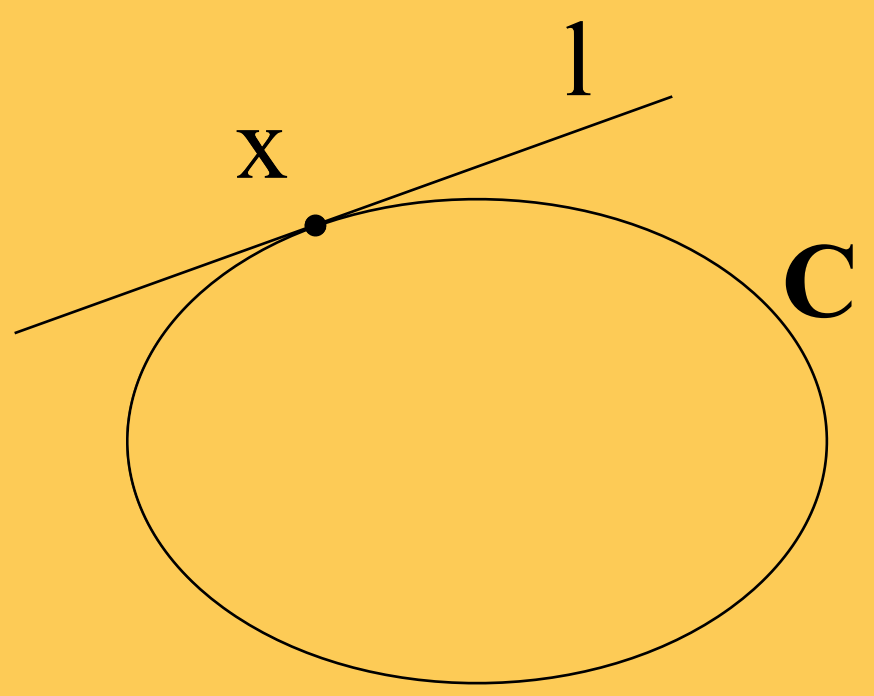
$$\mathrm{x}^{\mathsf{T}}\mathbf{C}\,\mathrm{x} = 0 \quad \text{with} \quad \mathbf{C} = \begin{bmatrix} a & b/2 & d/2 \\ b/2 & c & e/2 \\ d/2 & e/2 & f \end{bmatrix}$$



5DOF: $\{a : b : c : d : e : f\}$

TANGENT LINES TO CONICS

The line l tangent to $\mathbf{C}$ at point x on $\mathbf{C}$ is given by $\mathrm{l}=\mathbf{C}\mathrm{x}$

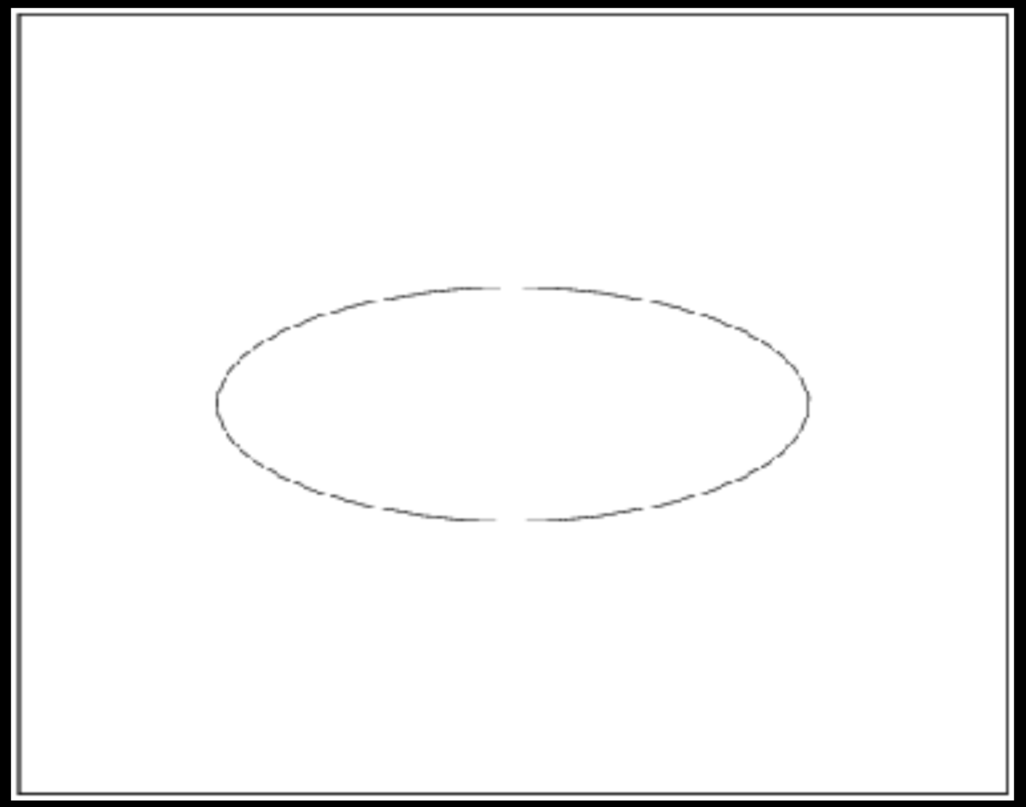


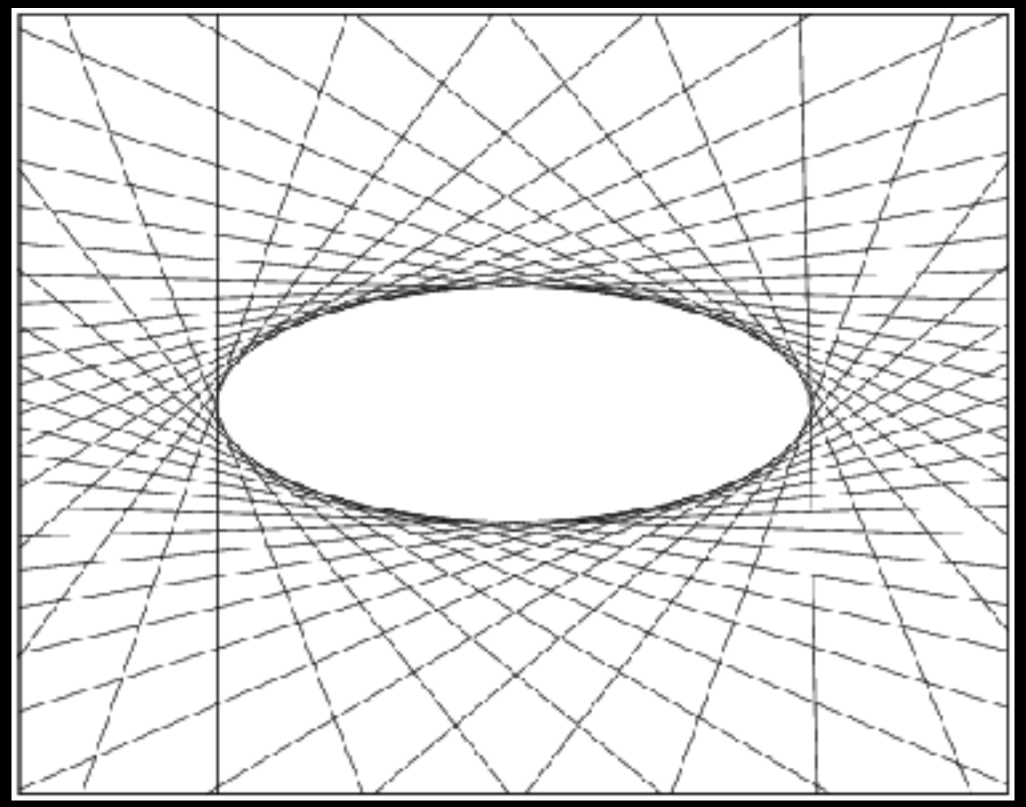
DUAL CONICS

A line tangent to the conic $\mathbf{C}$ satisfies $\mathbf{l}^{\mathsf{T}}\mathbf{C}^{*}\mathbf{l}=0$

In general ($\mathbf{C}$ full rank): $\mathbf{C}^{*}=\mathbf{C}^{-1}$

Dual conics = line conics = conic envelopes





PROJECTIVE TRANSFORMATIONS

Definition:

A *projectivity* is an invertible mapping h from P^2 to itself such that three points x_1,x_2,x_3 lie on the same line if and only if $h(x_1),h(x_2),h(x_3)$ do.

Theorem:

A mapping $h:P^2 \rightarrow P^2$ is a projectivity if and only if there exist a non-singular 3x3 matrix $\mathbf{H}$ such that for any point in P^2 represented by a vector x it is true that $h(x)=\mathbf{H}x$

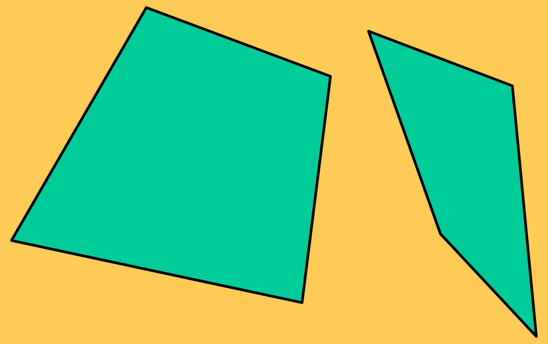
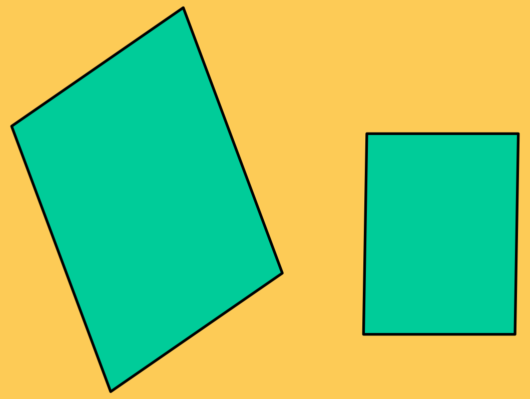
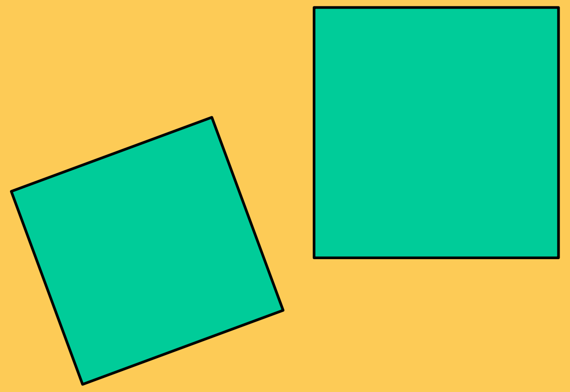
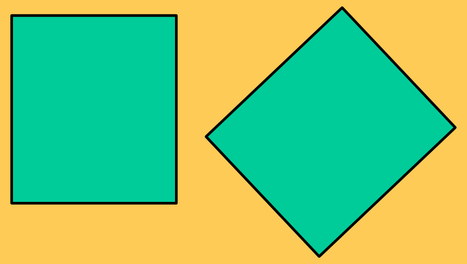
Definition: Projective transformation

$$\begin{pmatrix} x'_1 \\ x'_2 \\ x'_3 \end{pmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} \quad \text{or} \quad x' = \mathbf{H}\,x$$

8DOF

projectivity=collineation=projective transformation=homography

OVERVIEW TRANSFORMATIONS

Projective 8dof	$\begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix}$		Concurrency, collinearity, order of contact (intersection, tangency, inflection, etc.), cross ratio
Affine 6dof	$\begin{bmatrix} a_{11} & a_{12} & t_x \\ a_{21} & a_{22} & t_y \\ 0 & 0 & 1 \end{bmatrix}$		Parallellism, ratio of areas, ratio of lengths on parallel lines (e.g midpoints), linear combinations of vectors (centroids). **The line at infinity l_∞**
Similarity 4dof	$\begin{bmatrix} sr_{11} & sr_{12} & t_x \\ sr_{21} & sr_{22} & t_y \\ 0 & 0 & 1 \end{bmatrix}$		Ratios of lengths, angles. **The circular points I,J**
Euclidean 3dof	$\begin{bmatrix} r_{11} & r_{12} & t_x \\ r_{21} & r_{22} & t_y \\ 0 & 0 & 1 \end{bmatrix}$		lengths, areas.

3D POINTS

3D point

$\left(X,Y,Z\right)^{\mathsf{T}}$ in $\mathbf{R}^3$

$\mathrm{X} = \left(X_1, X_2, X_3, X_4\right)^{\mathsf{T}}$ in $\mathbf{P}^3$

$$\mathrm{X} = \left(\frac{X_1}{X_4}, \frac{X_2}{X_4}, \frac{X_3}{X_4}, 1\right)^{\mathsf{T}} = \left(X,Y,Z,1\right)^{\mathsf{T}} \qquad \left(X_4 \neq 0\right)$$

projective transformation

$$\mathrm{X}' = \mathbf{H}\,\mathrm{X} \quad \text{(4x4-1=15 dof)}$$

PLANES

3D plane

$$\pi_1 X + \pi_2 Y + \pi_3 Z + \pi_4 = 0$$

$$\pi_1 X_1 + \pi_2 X_2 + \pi_3 X_3 + \pi_4 X_4 = 0$$

$$\pi^\mathsf{T} \mathrm{X} = 0$$

Dual: points ↔ planes

Transformation

$$\mathrm{X}' = \mathbf{H}\,\mathrm{X}$$

$$\pi' = \mathbf{H}^{-\mathsf{T}}\,\pi$$

QUADRICS AND DUAL QUADRICS

- Quadric

  $X^T Q X = 0$ (Q : 4x4 symmetric matrix)

  $$Q = \begin{bmatrix} \bullet & \bullet & \bullet & \bullet \\ \boxed{?} & \bullet & \bullet & \bullet \\ \boxed{?} & \boxed{?} & \bullet & \bullet \\ \boxed{?} & \boxed{?} & \boxed{?} & \bullet \end{bmatrix}$$

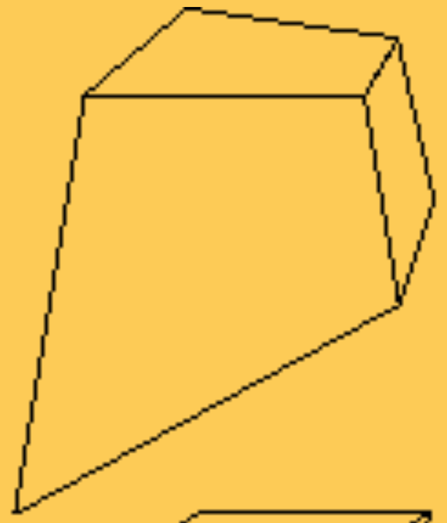
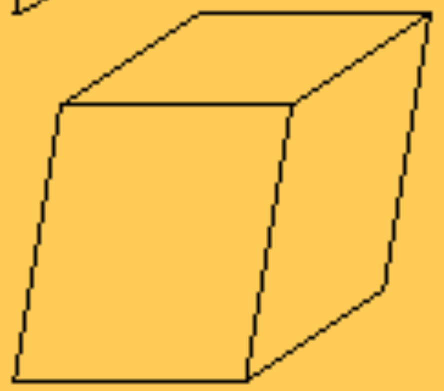
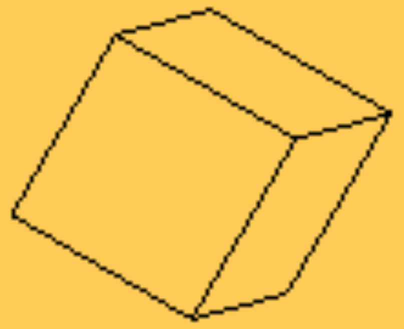
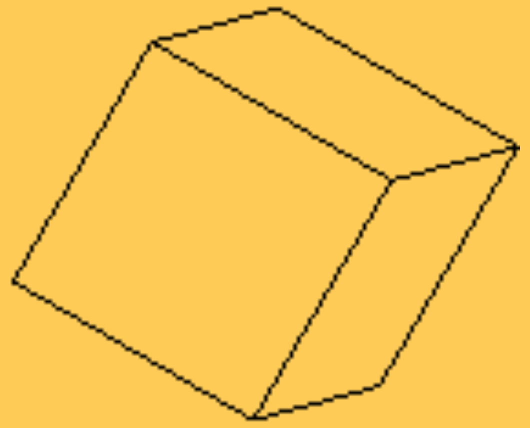
  1. 9 d.o.f.
  2. (plane ∩ quadric)=conic $C = M^T Q M$
  3. transformation $Q' = H^{-T} Q H^{-1}$

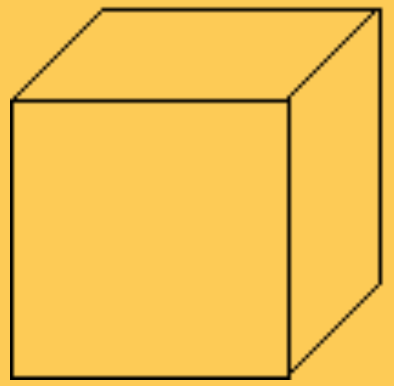
- Dual Quadric

  $\pi^T Q^* \pi = 0$

  1. relation to quadric $Q^* = Q^{-1}$ (non-degenerate)
  2. transformation $Q'^* = H Q^* H^T$

HIERARCHY OF TRANSFORMATIONS

Projective 15dof	$\begin{bmatrix} A & t \\ v^T & v \end{bmatrix}$		Intersection and tangency
Affine 12dof	$\begin{bmatrix} A & t \\ 0^T & 1 \end{bmatrix}$		Parallellism of planes, Volume ratios, centroids, **The plane at infinity π_∞**
Similarity 7dof	$\begin{bmatrix} sR & t \\ 0^T & 1 \end{bmatrix}$		**The absolute conic Ω_∞**
Euclidean 6dof	$\begin{bmatrix} R & t \\ 0^T & 1 \end{bmatrix}$		Volume



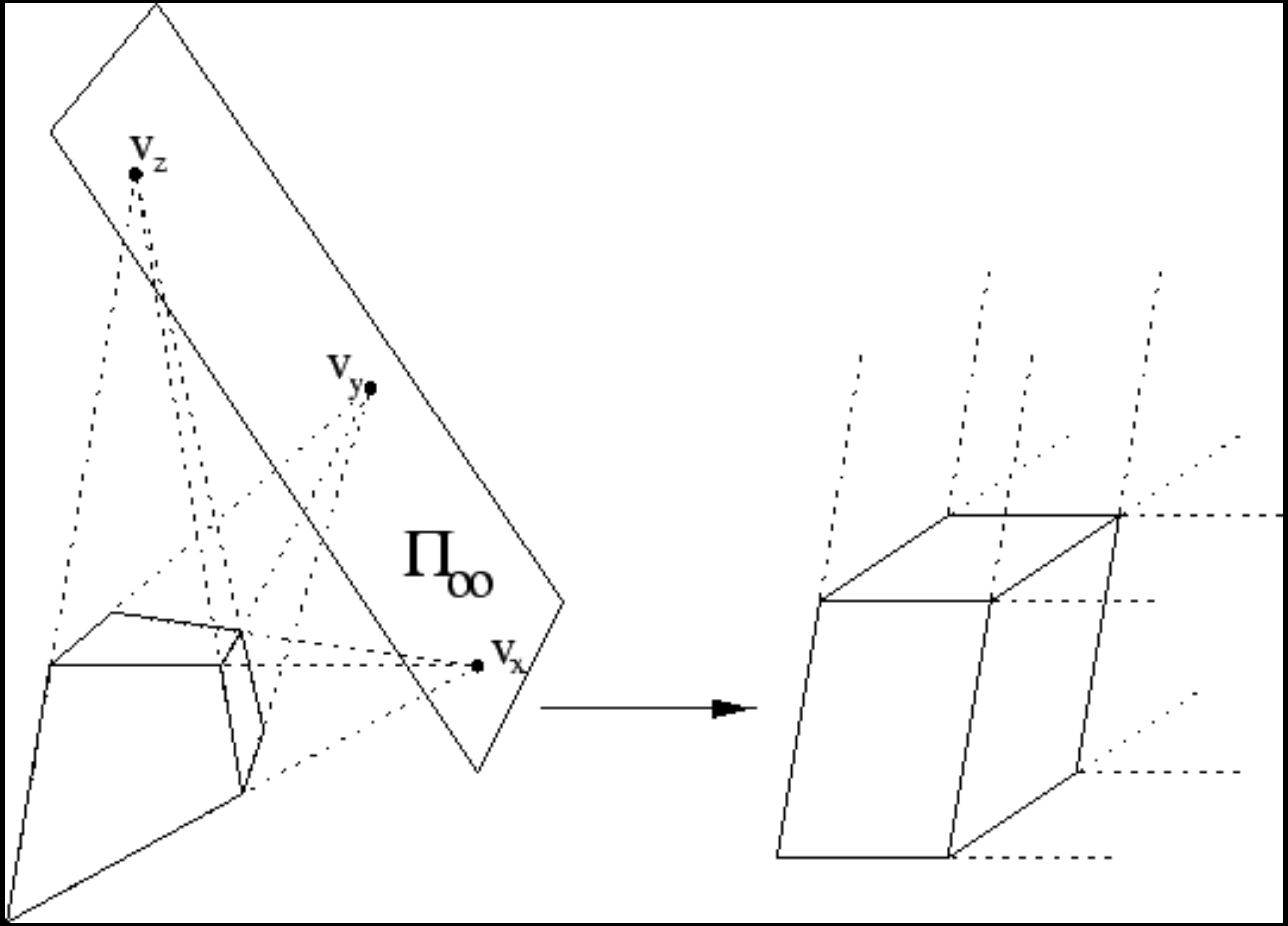
THE PLANE AT INFINITY

$$\pi'_\infty = \mathbf{H}_A^{-\mathsf{T}}\pi_\infty = \begin{bmatrix} \mathbf{A}^{-\mathsf{T}} & 0 \\ -\mathbf{A}\,\mathrm{t} & 1 \end{bmatrix} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} = \pi_\infty$$

The plane at infinity π_∞ is a fixed plane under a projective transformation H if H is an affinity

1. canical position $\pi_\infty = (0,0,0,1)^\mathsf{T}$
2. contains directions $\mathrm{D} = (X_1, X_2, X_3, 0)^\mathsf{T}$

THE PLANE AT INFINITY



THE ABSOLUTE CONIC

The absolute conic Ω_∞ is a (point) conic on π_∞.

In a metric frame:

$$\left.\begin{array}{c} X_1^2 + X_2^2 + X_3^2 \\ X_4 \end{array}\right\} = 0$$

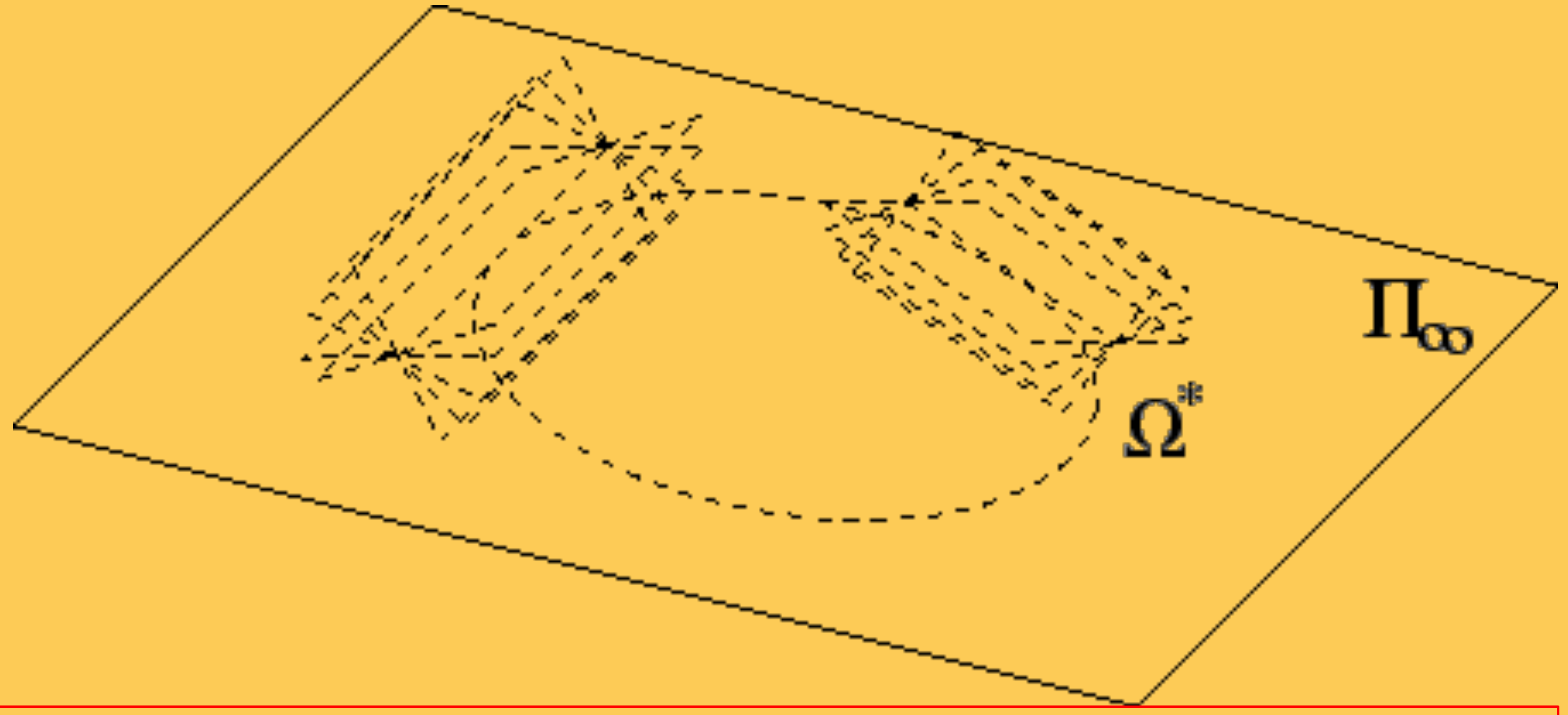
or conic for directions: $(X_1, X_2, X_3)\mathrm{I}(X_1, X_2, X_3)^\mathsf{T}$
(with no real points)

$$\boxed{\text{The absolute conic } \Omega_\infty \text{ is a fixed conic under the projective transformation } \mathbf{H} \text{ if } \mathbf{H} \text{ is a similarity}}$$

1. Ω_∞ is only fixed as a set
2. Circle intersect Ω_∞ in two points
3. Spheres intersect π_∞ in Ω_∞

THE DUAL ABSOLUTE QUADRIC

$$\Omega^*_\infty = \begin{bmatrix} I & 0 \\ 0^T & 0 \end{bmatrix}$$



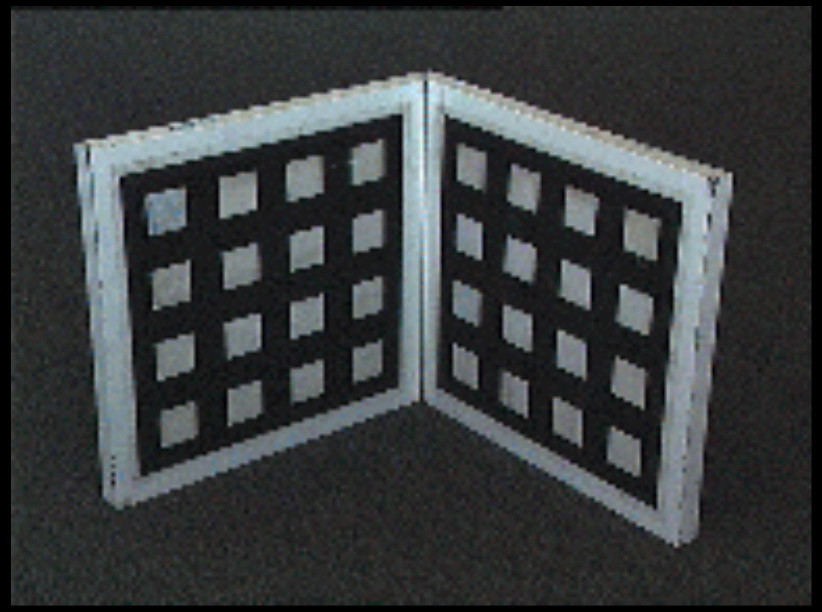
The absolute conic Ω^*_∞ is a fixed conic under the projective transformation $\mathbf{H}$ if $\mathbf{H}$ is a similarity

1. 8 dof
2. plane at infinity π_∞ is the nullvector of Ω_∞

SELF-CALIBRATION

MOTIVATION

- Avoid explicit calibration procedure
  - Complex procedure
  - Need for calibration object
  - Need to maintain calibration



MOTIVATION

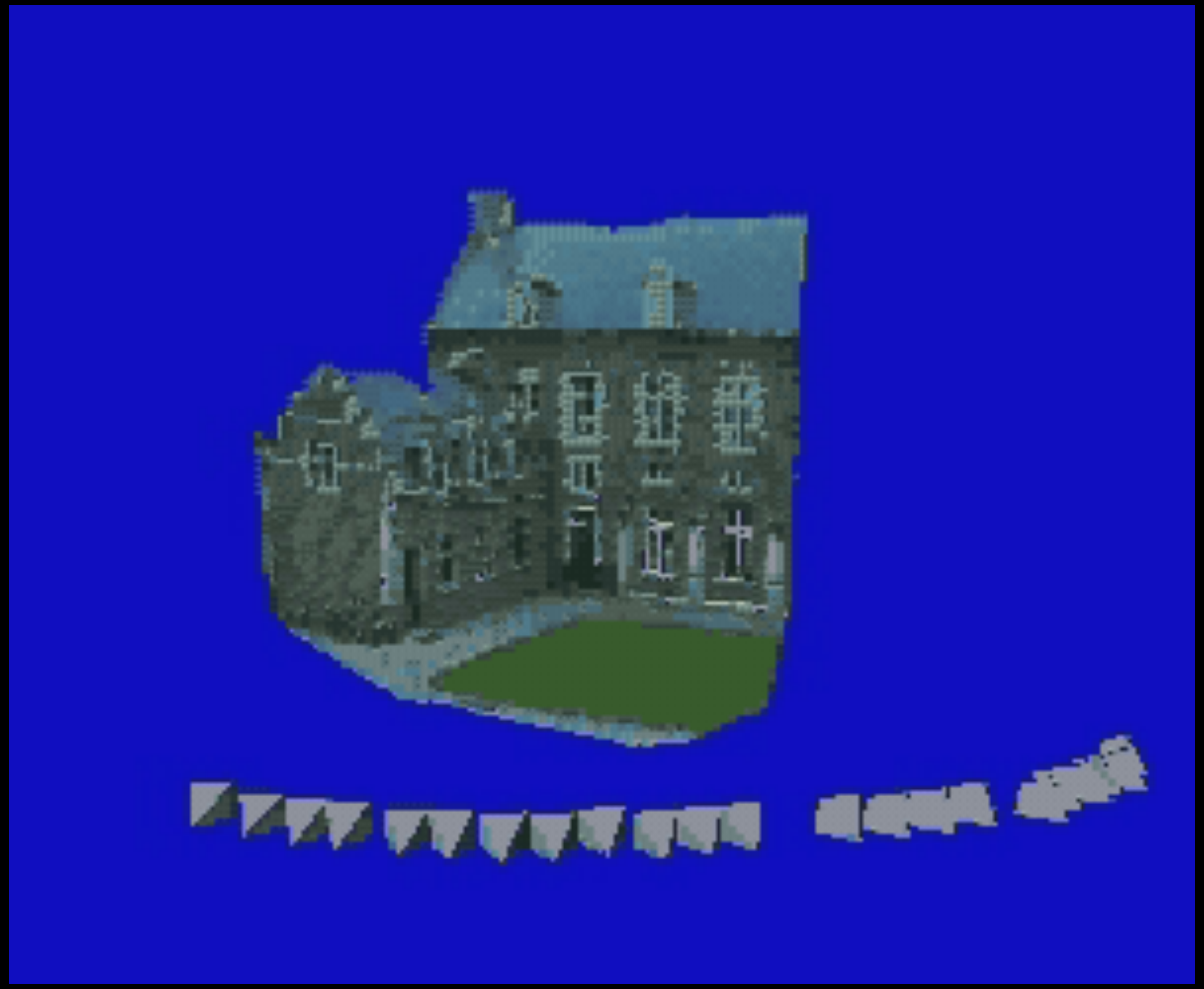
- Allow flexible acquisition
    - No prior calibration necessary
    - Possibility to vary intrinsics
    - Use archive footage

EXAMPLE

PROJECTIVE AMBIGUITY

Reconstruction from uncalibrated images

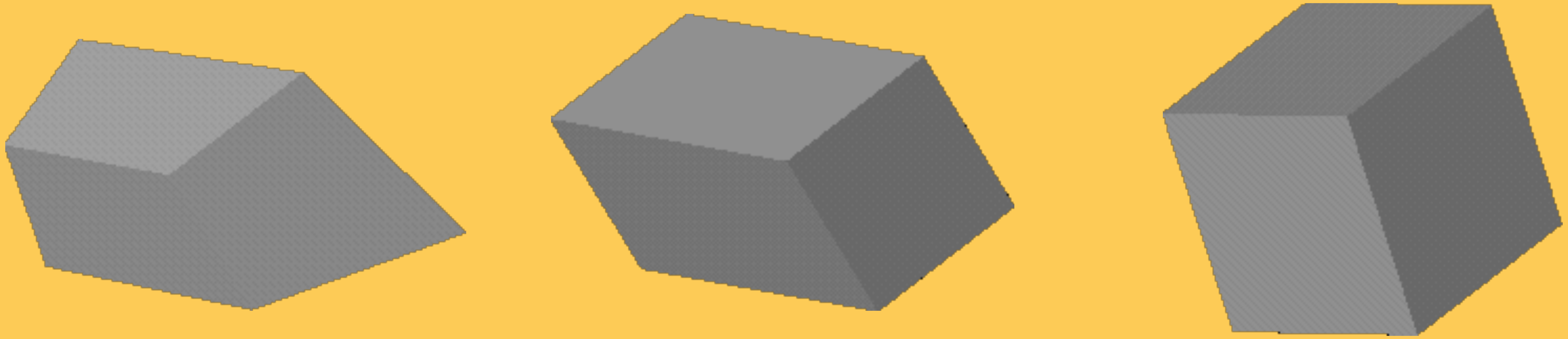
$\Rightarrow$ projective ambiguity on reconstruction



$$m = \mathbf{P}M = (\mathbf{P}\mathbf{T}^{-1})(\mathbf{T}M) = \mathbf{P}'M'$$

STRATIFICATION OF GEOMETRY

Projective | **Affine** | **Metric**



15 DOF

12 DOF
plane at infinity
parallelism

7 DOF
absolute conic
angles, rel.dist.

More general ←

More structure →

CONSTRAINTS ?

- Scene constraints
  - Parallellism, vanishing points, horizon, ...
  - Distances, positions, angles, ...

  Unknown scene → no constraints

- Camera extrinsics constraints
  – Pose, orientation, ...

  Unknown camera motion → no constraints

- Camera intrinsics constraints
  – Focal length, principal point, aspect ratio & skew

  Perspective camera model too general
  → some constraints

EUCLIDEAN PROJECTION MATRIX

Factorization of Euclidean projection matrix

$$\mathbf{P} = \mathbf{K}\left[\mathbf{R}^{\top} \mid -\mathbf{R}^{\top}\mathbf{t}\right]$$

Intrinsics: $\mathbf{K} = \begin{bmatrix} f_x & s & u_x \\ & f_y & u_y \\ & & 1 \end{bmatrix}$ (camera geometry)

Extrinsics: $(\mathbf{R}, \mathrm{t})$ (camera motion)

Note: every projection matrix can be factorized,
but only meaningful for euclidean projection matrices

CONSTRAINTS ON INTRINSIC PARAMETERS

$$\mathbf{K} = \begin{bmatrix} f_x & s & u_x \\ & f_y & u_y \\ & & 1 \end{bmatrix}$$

Constant

e.g. fixed camera: $\mathbf{K}_1 = \mathbf{K}_2 = \boxed{?}$

Known

e.g. rectangular pixels: $s = 0$

square pixels: $f_x = f_y, s = 0$

principal point known: $(u_x, u_y) = \left(\frac{w}{2}, \frac{h}{2}\right)$

SELF-CALIBRATION

Upgrade from projective structure to metric structure using constraints on intrinsic camera parameters

- Constant intrinsics

(Faugeras et al. ECCV´92, Hartley´93, Triggs´97, Pollefeys et al. PAMI´98, ...)

- Some known intrinsics, others varying

(Heyden&Astrom CVPR´97, Pollefeys et al. ICCV´98,...)

- Constraints on intrincs and restricted motion

(Moons et al.´94, Hartley ´94, Armstrong ECCV´96, ...)

(e.g. pure translation, pure rotation, planar motion)

A COUNTING ARGUMENT

- To go from projective (15DOF) to metric (7DOF) at least 8 constraints are needed
- Minimal sequence length should satisfy

$$n \times (\#\,known) + (n-1) \times (\#\,fixed) \geq 8$$

- Independent of algorithm
- Assumes general motion (i.e. not critical)

SELF-CALIBRATION: CONCEPTUAL ALGORITHM

Given projective structure and motion $\{\mathbf{P}_j, \mathbf{M}_i\}$, then the metric structure and motion can be obtained as $\{\mathbf{P}_j\mathbf{T}^{-1}, \mathbf{T}\mathbf{M}_i\}$, with

$$\mathbf{T} = \arg\min_{\mathbf{T}} C\left(K\left(\mathbf{P}_1\mathbf{T}^{-1}\right), K\left(\mathbf{P}_2\mathbf{T}^{-1}\right), \boxed{?}, K\left(\mathbf{P}_n\mathbf{T}^{-1}\right)\right)$$

$C\left(\mathbf{K}_1, \mathbf{K}_2, \boxed{?}, \mathbf{K}_n\right)$ criterium expressing constraints

$K(\mathbf{P})$ function extracting intrinsics from projection matrix

TEXT

CONICS & QUADRICS

CONICS

$$m^T C m = 0 \qquad l^T C^* l = 0$$

$$C^* = C^{-1}$$

QUADRICS

$$M^T Q M = 0 \qquad \Pi^T Q^* \Pi = 0$$

$$Q^* = Q^{-1}$$

TRANSFORMATIONS

$$C \boxed{?} C' \sim H^{-T} C H^{-1}$$

$$C^* \boxed{?} C^{*\prime} \sim H C^* H^T$$

$$Q \boxed{?} Q' \sim T^{-T} Q T^{-1}$$

$$Q^* \boxed{?} Q^{*\prime} \sim T Q^* T^T$$

PROJECTION

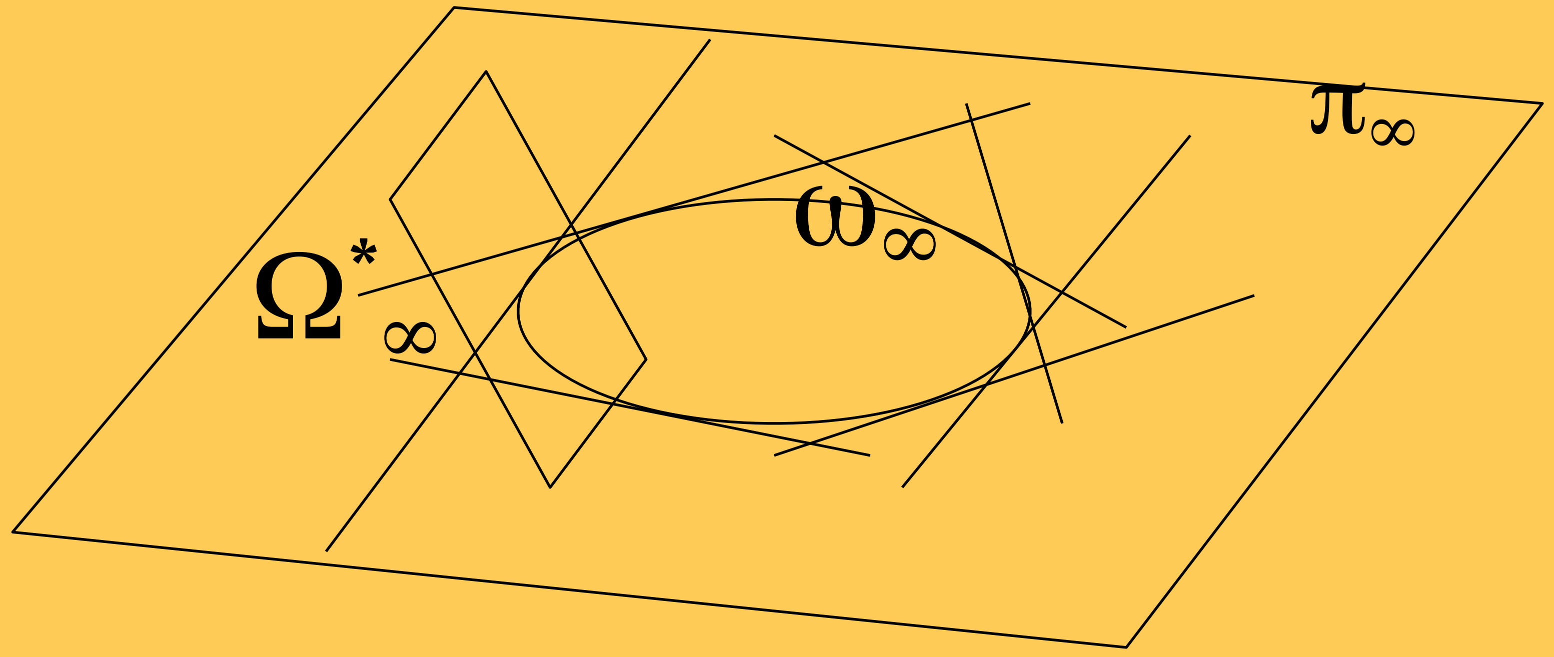
$$C^* \sim P Q^* P^T$$

THE ABSOLUTE DUAL QUADRIC

(Triggs CVPR´97)

Degenerate dual quadric Ω^*_∞

Encodes both absolute conic ω_∞ and π_∞



for metric frame: $$\pi^\mathsf{T} \begin{bmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{0}^\mathsf{T} & 0 \end{bmatrix} \pi = 0$$

ABSOLUTE DUAL QUADRIC AND SELF-CALIBRATION

Eliminate extrinsics from equation

$$\mathbf{K}\left[\mathbf{R}^{\mathsf{T}} \quad \cancel{-\mathbf{R}^{\mathsf{T}}\mathbf{t}}\right] \longrightarrow \mathbf{K}\cancel{\mathbf{R}^{\mathsf{T}}\mathbf{R}}\mathbf{K}^{\mathsf{T}} \longrightarrow \mathbf{K}\mathbf{K}^{\mathsf{T}}$$

Equivalent to projection of dual quadric

$$\mathbf{P}\Omega^{*}_{\infty}\mathbf{P}^{\mathsf{T}} \propto \mathbf{K}\mathbf{K}^{\mathsf{T}} \qquad \Omega^{*}_{\infty} = \mathrm{diag}(1110)$$

Abs.Dual Quadric also exists in projective world

$$\mathbf{K}\mathbf{K}^{\mathsf{T}} \propto \mathbf{P}\Omega^{*}_{\infty}\mathbf{P}^{\mathsf{T}} \propto (\mathbf{P}\mathbf{T}^{-1})(\mathbf{T}\Omega^{*}_{\infty}\mathbf{T}^{\mathsf{T}})(\mathbf{T}^{-\mathsf{T}}\mathbf{P}^{\mathsf{T}})$$

$$\propto \mathbf{P}'\Omega'^{*}_{\infty}\mathbf{P}'^{\mathsf{T}}$$

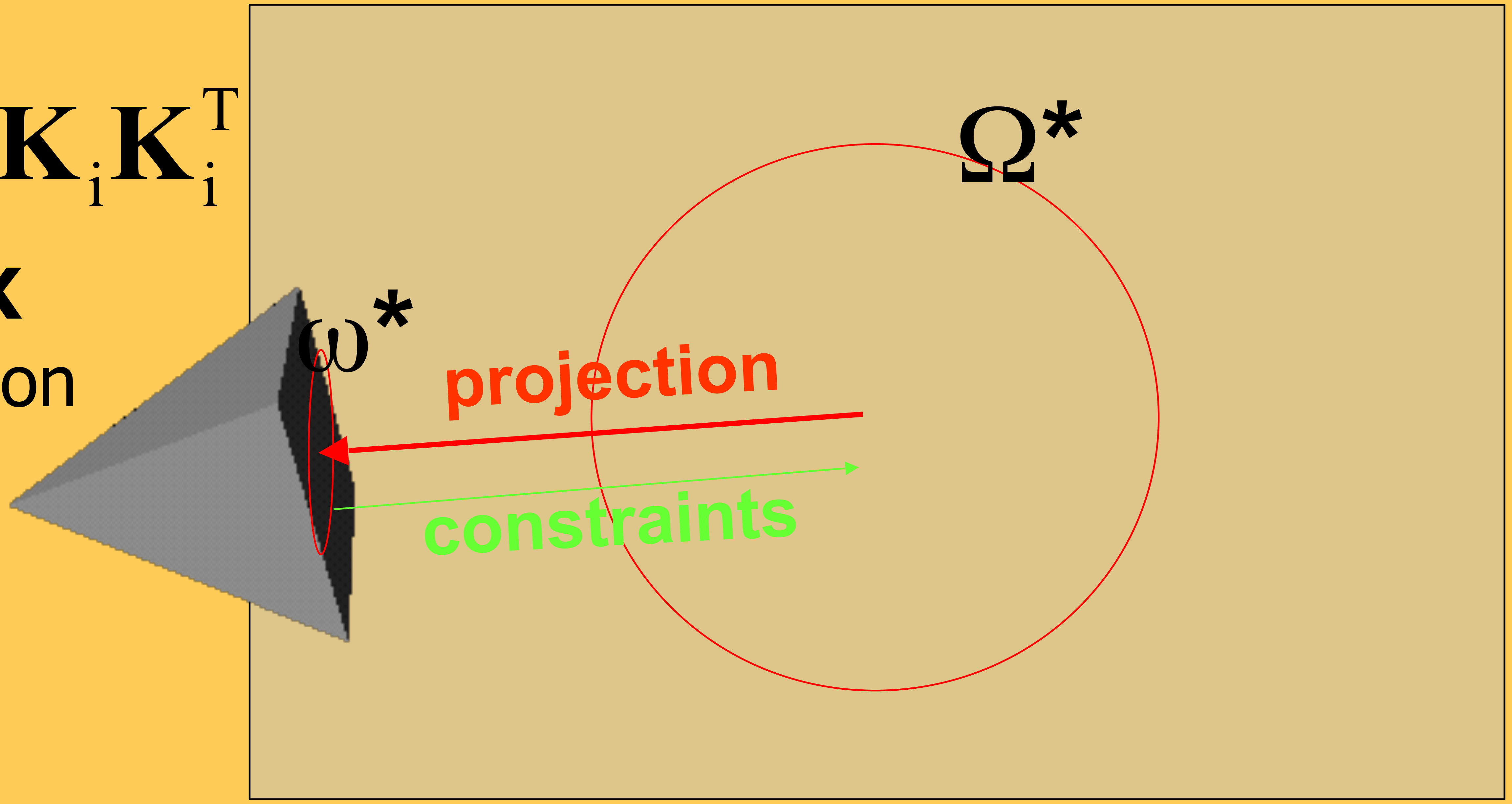
Transforming world so that $\Omega'^{*}_{\infty} \rightarrow \Omega^{*}_{\infty}$
reduces ambiguity to metric

IMAGE OF THE ABSOLUTE CONIC

Projection equation:

$$\omega_i^* \propto P_i \Omega^* P_i^T \propto K_i K_i^T$$

Translate constraints on **K** through projection equation to constraints on Ω*



Absolute conic = calibration object which is always present but can only be observed through constraints on the intrinsics

CONSTRAINTS ON Ω^*_∞

$$\omega^*_\infty = \begin{bmatrix} f_x^2 + s^2 + c_x^2 & sf_y + c_x c_y & c_x \\ sf_y + c_x c_y & f_y^2 + c_y^2 & c_y \\ c_x & c_y & 1 \end{bmatrix}$$

condition	constraint	type	#constraints
Zero skew	$\omega^*_{12}\omega^*_{33} = \omega^*_{13}\omega^*_{23}$	quadratic	m
Principal point	$\omega^*_{13} = \omega^*_{23} = 0$	linear	$2m$
Zero skew (& p.p.)	$\omega^*_{12} = 0$	linear	m
Fixed aspect ratio (& p.p.& Skew)	$\omega^*_{11}\omega'^*_{22} = \omega^*_{22}\omega'^*_{11}$	quadratic	m-1
Known aspect ratio (& p.p.& Skew)	$\omega^*_{11} = \omega^*_{22}$	linear	m
Focal length (& p.p. & Skew)	$\omega^*_{33} = \omega^*_{11}$	linear	m

LINEAR ALGORITHM

(Pollefeys et al.,ICCV´98/IJCV´99)

Assume everything known, except focal length

$$\omega^* \approx \begin{bmatrix} \hat{f}^2 & 0 & 0 \\ 0 & \hat{f}^2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \propto \mathbf{P}\Omega^*\mathbf{P}^\top$$

$$\left(\mathbf{P}\Omega^*\mathbf{P}^\top\right)_{11} - \left(\mathbf{P}\Omega^*\mathbf{P}^\top\right)_{22} = 0$$
$$\left(\mathbf{P}\Omega^*\mathbf{P}^\top\right)_{12} = 0$$
$$\left(\mathbf{P}\Omega^*\mathbf{P}^\top\right)_{13} = 0$$
$$\left(\mathbf{P}\Omega^*\mathbf{P}^\top\right)_{23} = 0$$

Yields 4 constraint per image

Note that rank-3 constraint is not enforced

FIRST NORMALISE P BY KN

$$\mathbf{P}_N = \mathbf{K}_N^{-1}\mathbf{P} \text{ with } \mathbf{K}_N = \begin{bmatrix} w+h & 0 & \frac{w}{2} \\ & w+h & \frac{h}{2} \\ & & 1 \end{bmatrix}$$

$$\omega^* \sim \mathbf{K}\mathbf{K}^\top = \begin{bmatrix} f^2+s^2+u^2 & srf+uv & u \\ srf+uv & r^2f^2+v^2 & v \\ u & v & 1 \end{bmatrix} \approx \begin{bmatrix} 1\pm 9 & \pm 0.01 & \pm 0.1 \\ \pm 0.01 & 1\pm 9 & \pm 0.1 \\ \pm 0.1 & \pm 0.1 & 1 \end{bmatrix}$$

LINEAR ALGORITHM REVISITED

(Pollefeys et al., ECCV'02)

Weighted linear equations

$$\mathbf{K}\mathbf{K}^\top \approx \begin{bmatrix} \hat{f}^2 & 0 & 0 \\ 0 & \hat{f}^2 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\hat{f} \approx 1$$

$$\frac{1}{0.2}\left(\left(\mathbf{P}\Omega^*\mathbf{P}^\top\right)_{11} - \left(\mathbf{P}\Omega^*\mathbf{P}^\top\right)_{22}\right) = 0$$

$$\frac{1}{0.01}\left(\mathbf{P}\Omega^*\mathbf{P}^\top\right)_{12} = 0$$

$$\frac{1}{0.1}\left(\mathbf{P}\Omega^*\mathbf{P}^\top\right)_{13} = 0$$

$$\frac{1}{0.1}\left(\mathbf{P}\Omega^*\mathbf{P}^\top\right)_{23} = 0$$

$$\frac{1}{9}\left(\left(\mathbf{P}\Omega^*\mathbf{P}^\top\right)_{11} - \left(\mathbf{P}\Omega^*\mathbf{P}^\top\right)_{33}\right) = 0$$

$$\frac{1}{9}\left(\left(\mathbf{P}\Omega^*\mathbf{P}^\top\right)_{22} - \left(\mathbf{P}\Omega^*\mathbf{P}^\top\right)_{33}\right) = 0$$

PROJECTIVE TO METRIC

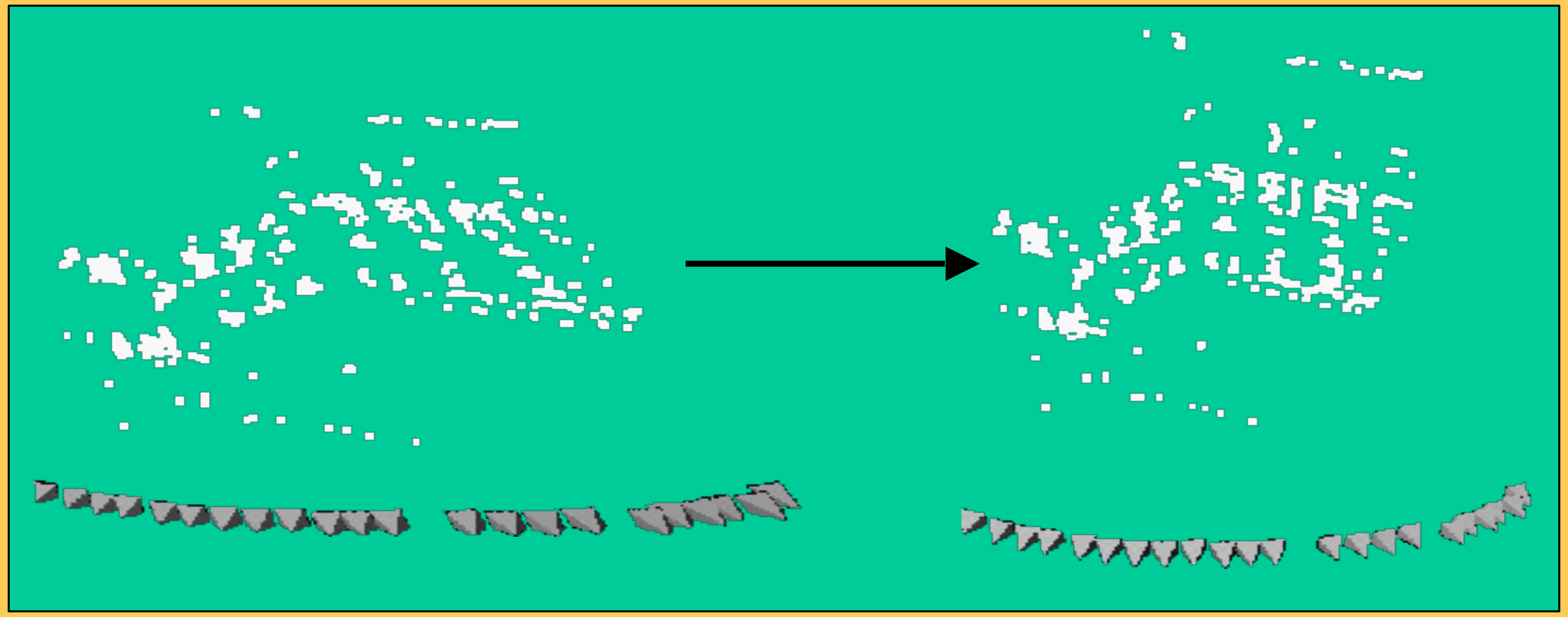
Compute $\mathbf{T}$ from

$$\tilde{\mathbf{I}} = \mathbf{T}\Omega^*_\infty\mathbf{T}^\top \text{ or } \mathbf{T}^{-1}\tilde{\mathbf{I}}\mathbf{T}^{-\top} = \Omega^*_\infty \text{ with } \tilde{\mathbf{I}} = \begin{bmatrix} \mathbf{I} & 0 \\ 0^\top & 0 \end{bmatrix}$$

using eigenvalue decomposition of Ω^*_∞

and then obtain metric reconstruction as

$$\mathbf{PT}^{-1} \text{ and } \mathbf{TM}$$



CRITICAL MOTION SEQUENCES

(Sturm, CVPR´97, Kahl, ICCV´99, Pollefeys,PhD´99)

- Self-calibration depends on camera motion
- Motion sequence is not always general enough
- Critical Motion Sequences have more than one potential absolute conic satisfying all constraints
- Possible to derive classification of CMS

CRITICAL MOTION SEQUENCES: ALGORITHM DEPENDENT

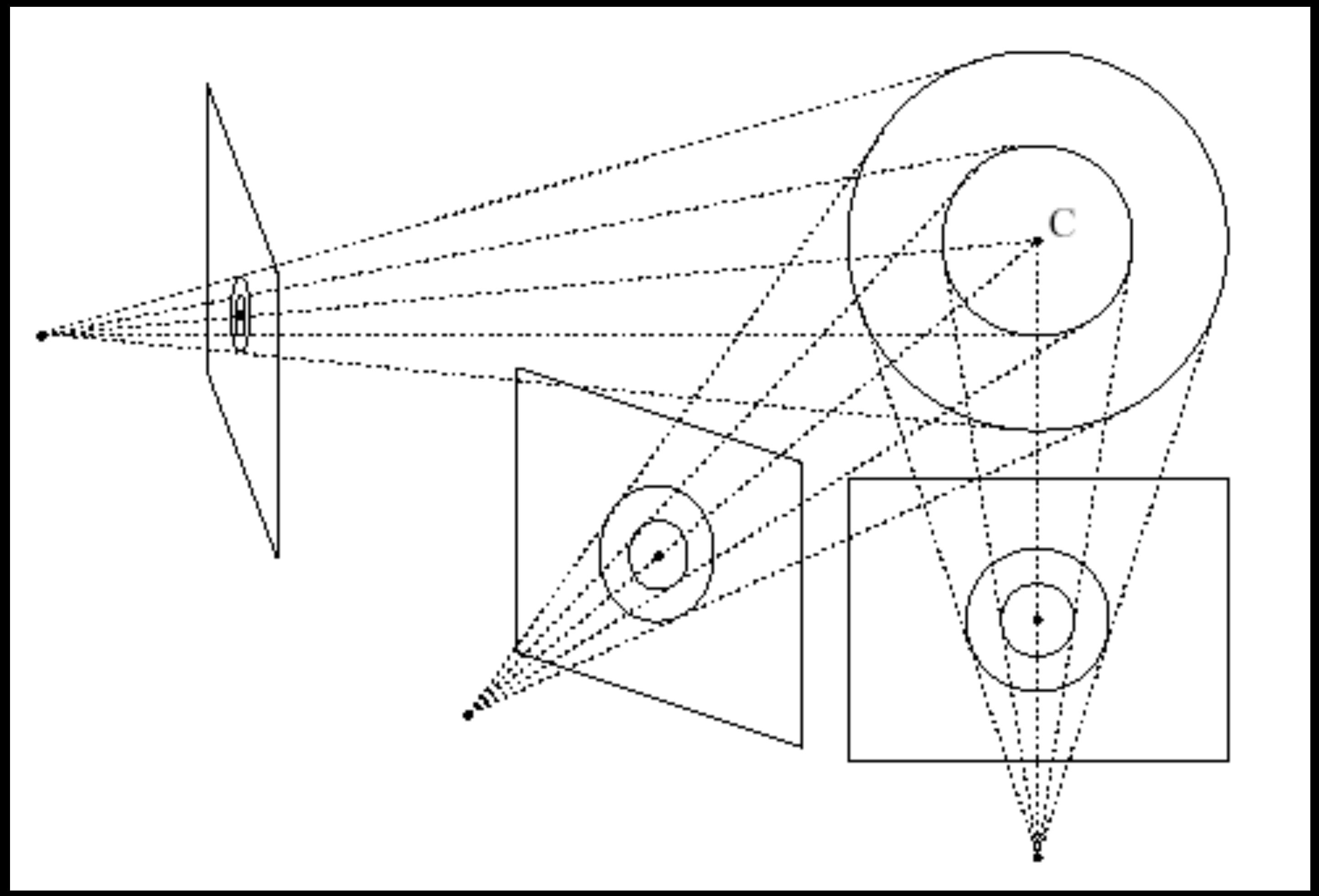
Additional critical motion sequences can exist for some specific algorithms

- when not all constraints are enforced

(e.g. not imposing rank 3 constraint)

- Kruppa equations/linear algorithm: fixating a point

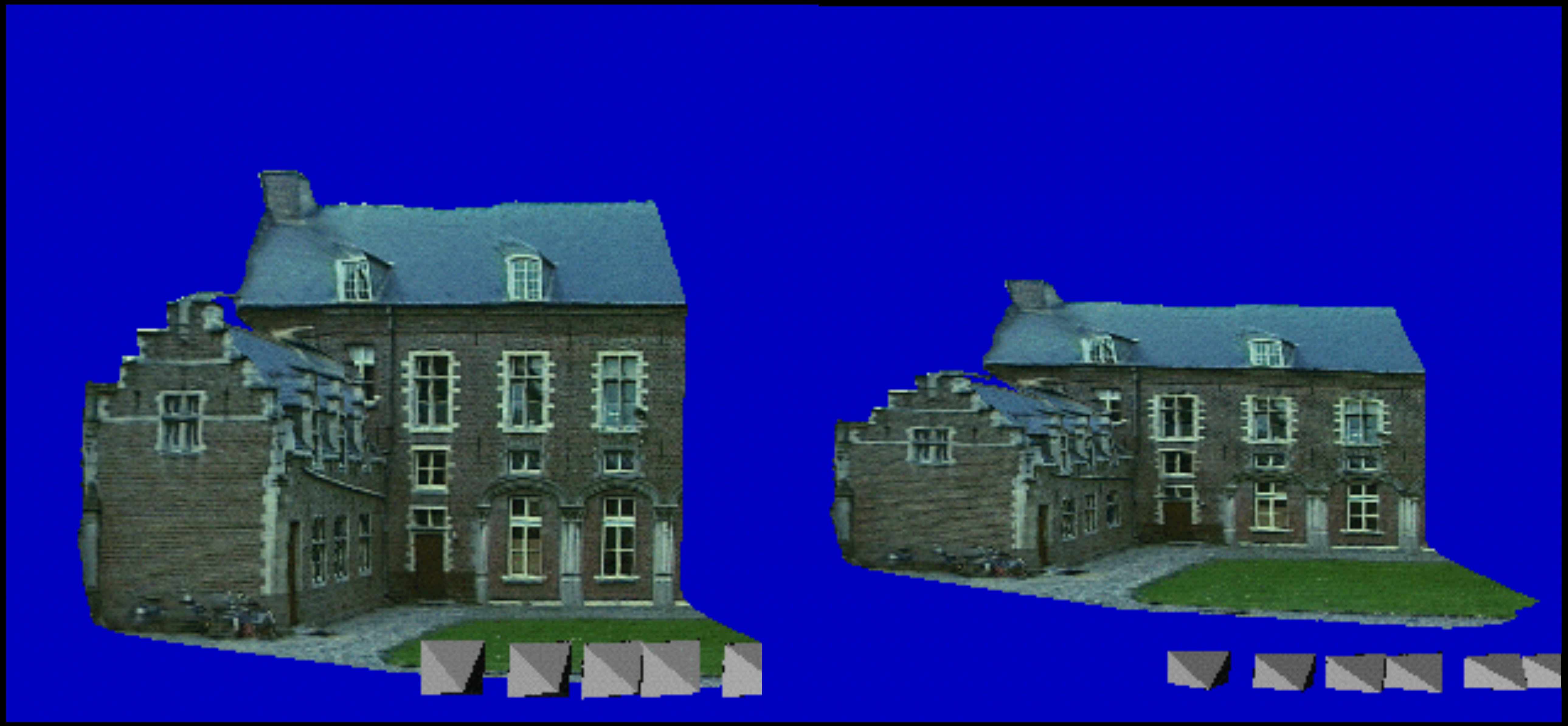
Some spheres also project to circles located in the image and hence satisfy all the linear/kruppa self-calibration constraints



NON-AMBIGUOUS NEW VIEWS FOR CMS

(Pollefeys,ICCV´01)

- restrict motion of virtual camera to CMS
- use (wrong) computed camera parameters



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- http://www.cs.unc.edu/~marc/tutorial/node76.html
- R. Hartley and A. Zisserman, Multiple View Geometry in Computer Vision, chapter 19.