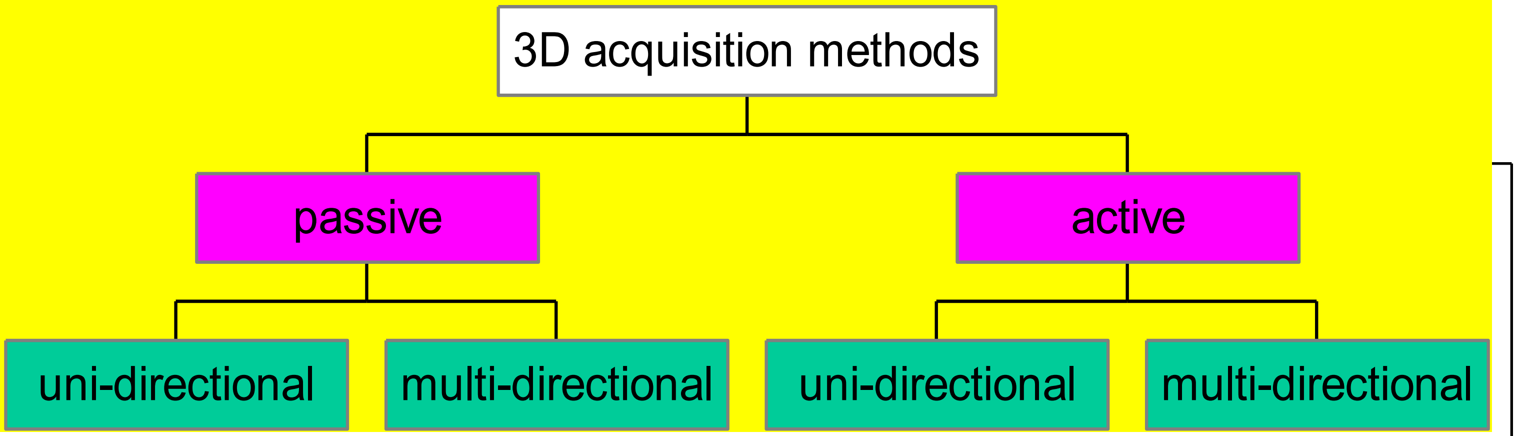
3D acquisition

3D acquisition taxonomy



3D acquisition methods

- passive
  - uni-directional
  - multi-directional
- active
  - uni-directional
  - multi-directional

Shape-from
- **texture**
- **contour**
- **silhouettes**
- **defocus**
- **shading**

Stereo

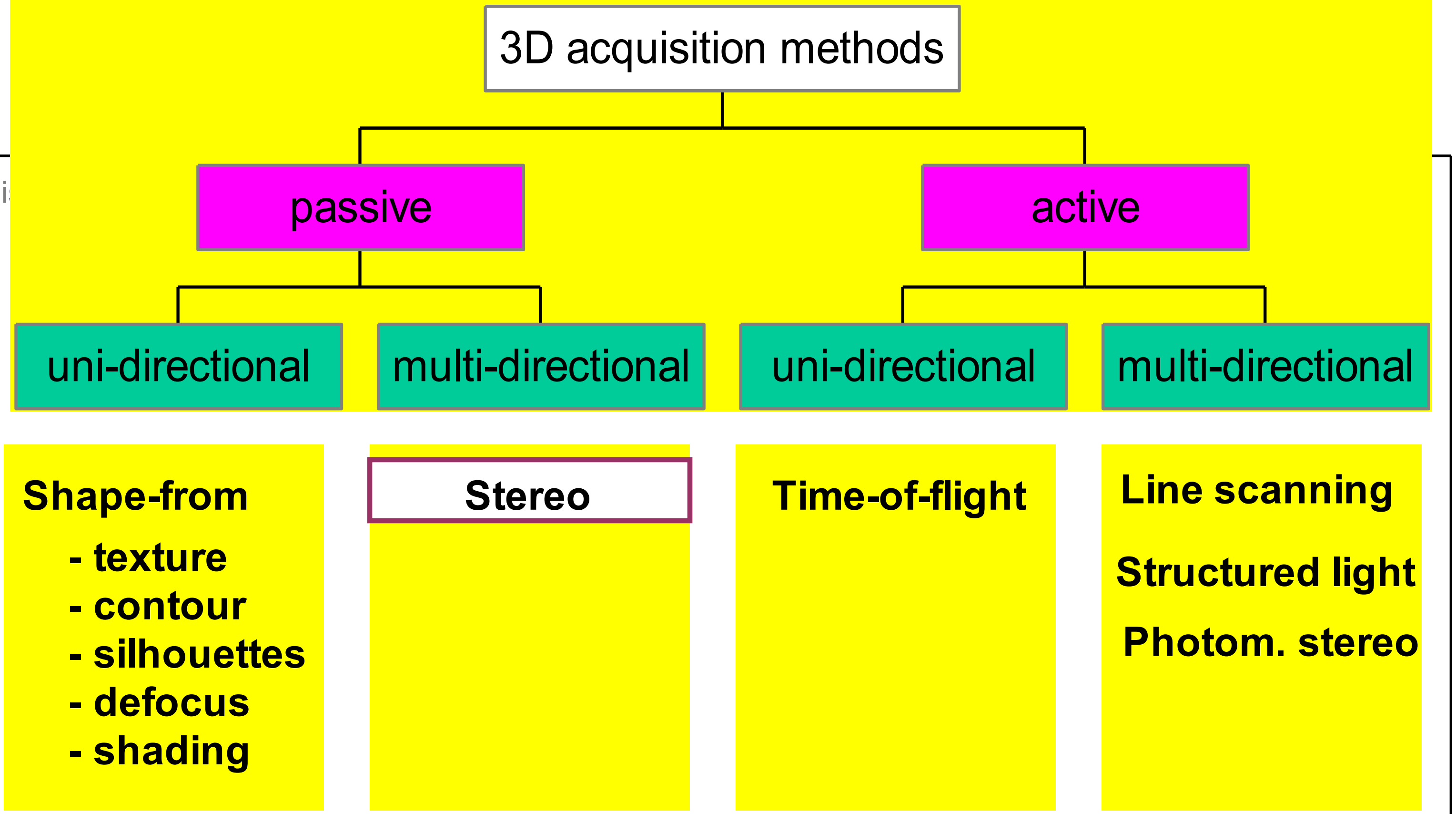
Time-of-flight

Line scanning

Structured light

Photom. stereo

3D acquisition taxonomy



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Structured light

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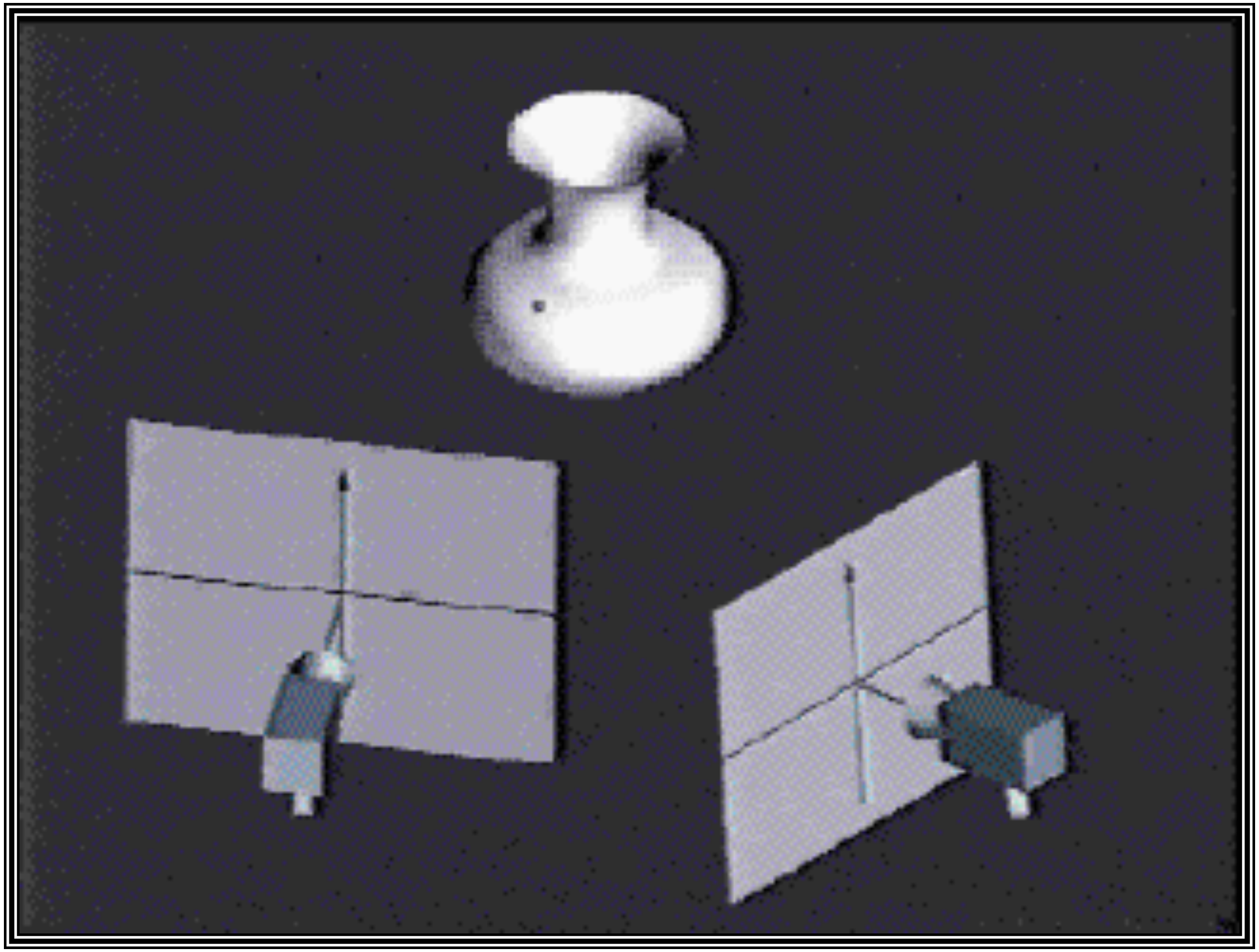
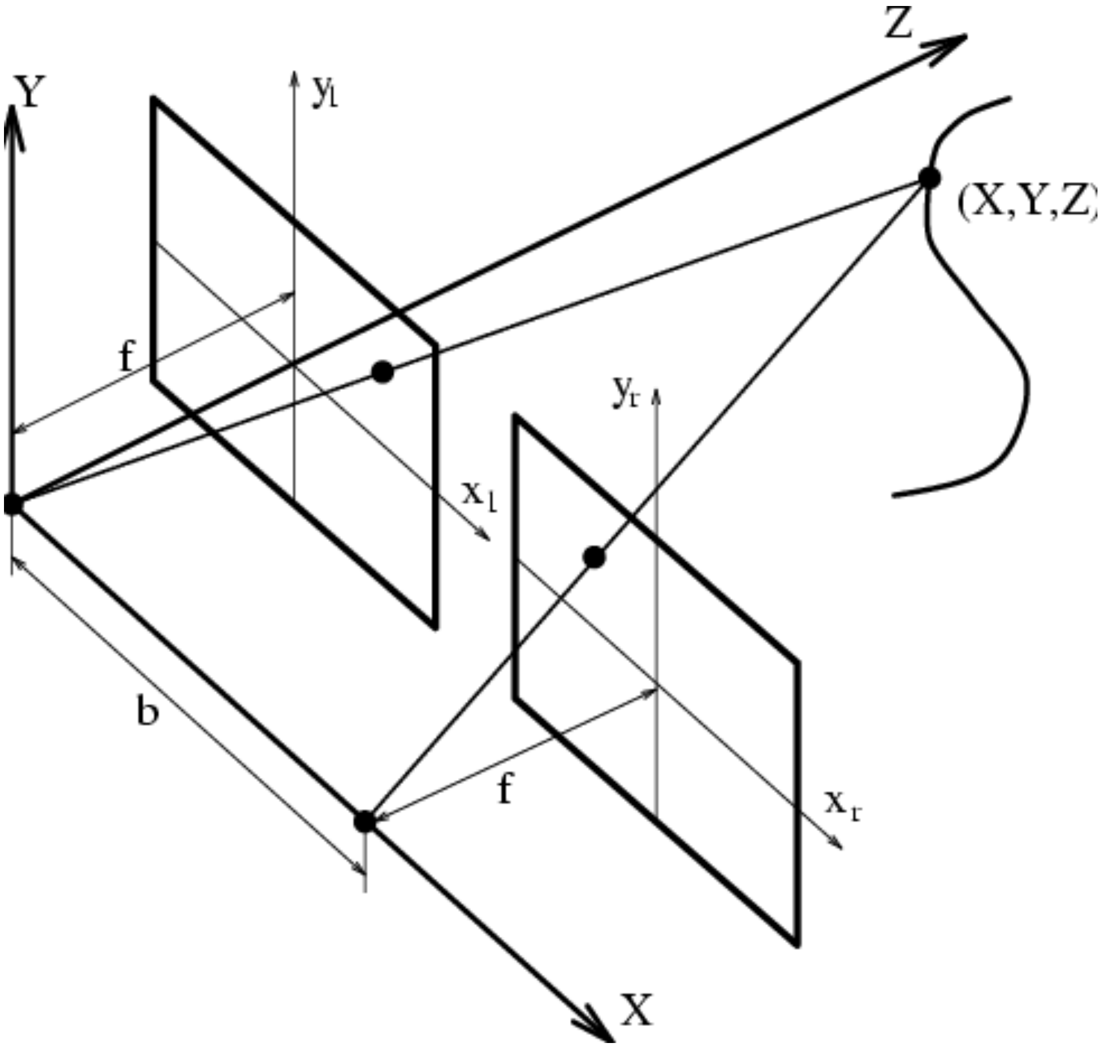
Stereo

The underlying principle is "triangulation" :

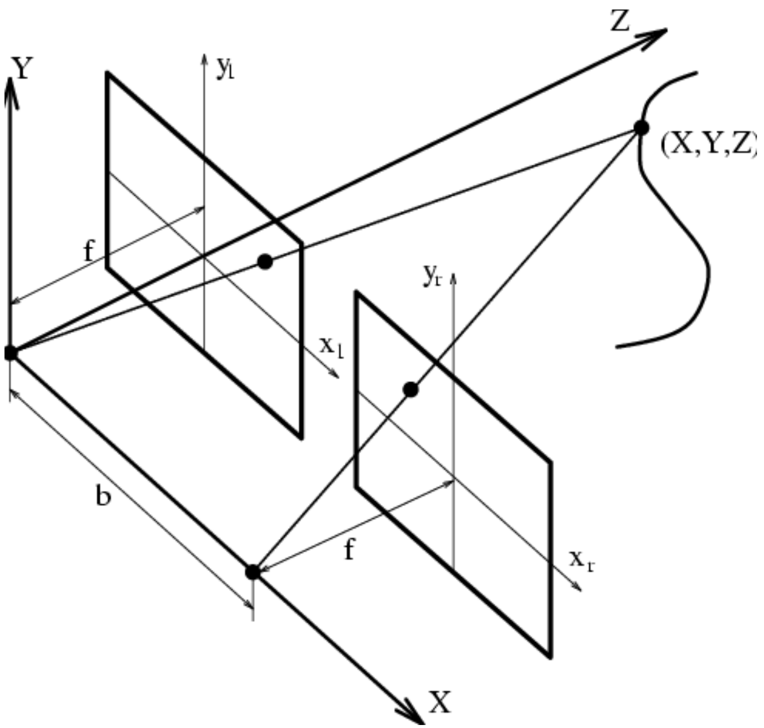


(Passive) stereo

Simple configuration :

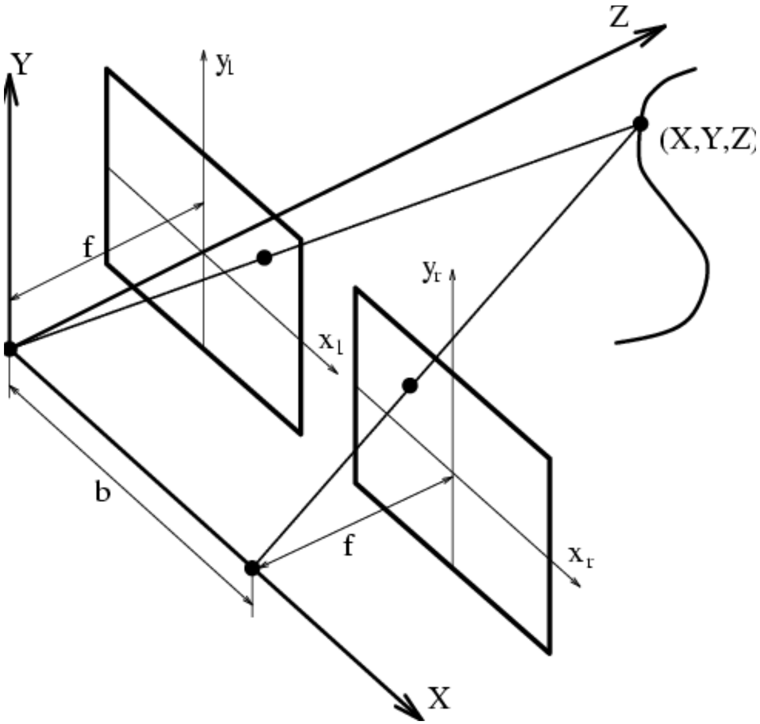


A simple stereo setup



- identical cameras
- coplanar image planes
- aligned *x*-axes

A simple stereo setup



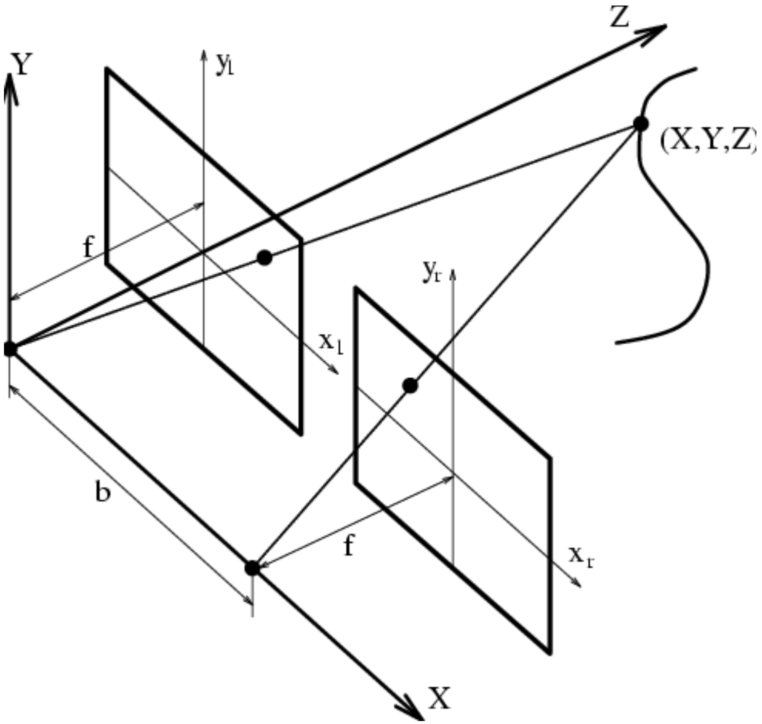
Reminder :

the camera projection can be formulated as

$$\boxed{\rho p = KR^t(P - C)}$$ for some non-zero $\rho \in \mathbb{R}$

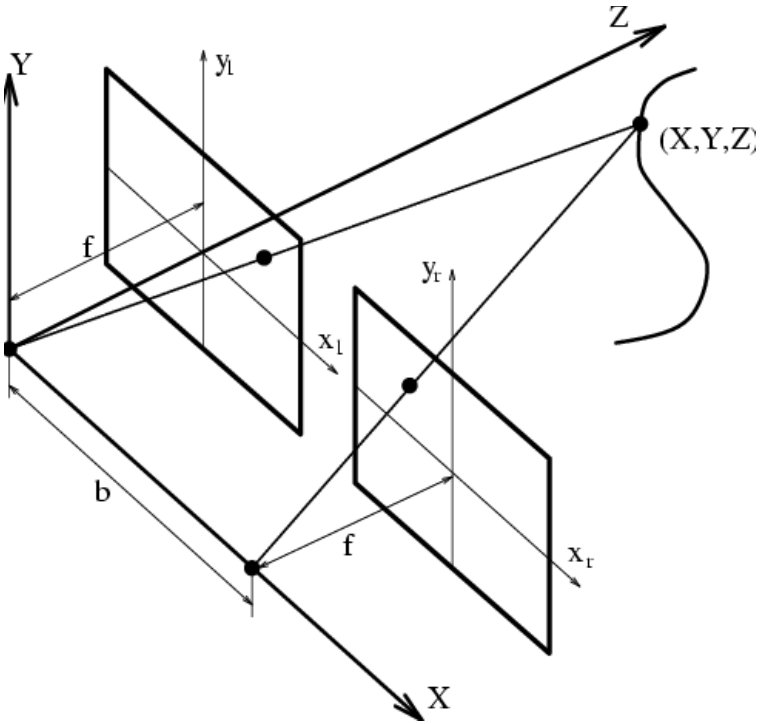
Here R is the identity...

A simple stereo setup



$$\rho\begin{pmatrix}x\\y\\1\end{pmatrix}=K\begin{pmatrix}X\\Y\\Z\end{pmatrix}\qquad \rho'\begin{pmatrix}x'\\y'\\1\end{pmatrix}=K\begin{pmatrix}X-b\\Y\\Z\end{pmatrix}\qquad K=\begin{pmatrix}fk_x & 0 & 0\\0 & fk_y & 0\\0 & 0 & 1\end{pmatrix}$$

A simple stereo setup



$$\begin{cases} x = \dfrac{fk_x X}{Z}, \\ y = \dfrac{fk_y Y}{Z}, \end{cases} \text{ and } \begin{cases} x' = \dfrac{fk_x (X - b)}{Z}, \\ y' = \dfrac{fk_y Y}{Z}, \end{cases}$$

Note that $y = y'$

A simple stereo setup

The 3D coordinates of the point are

$$X = b\frac{x}{(x - x')},$$

$$Y = b\frac{k_x}{k_y}\frac{y}{(x - x')},$$

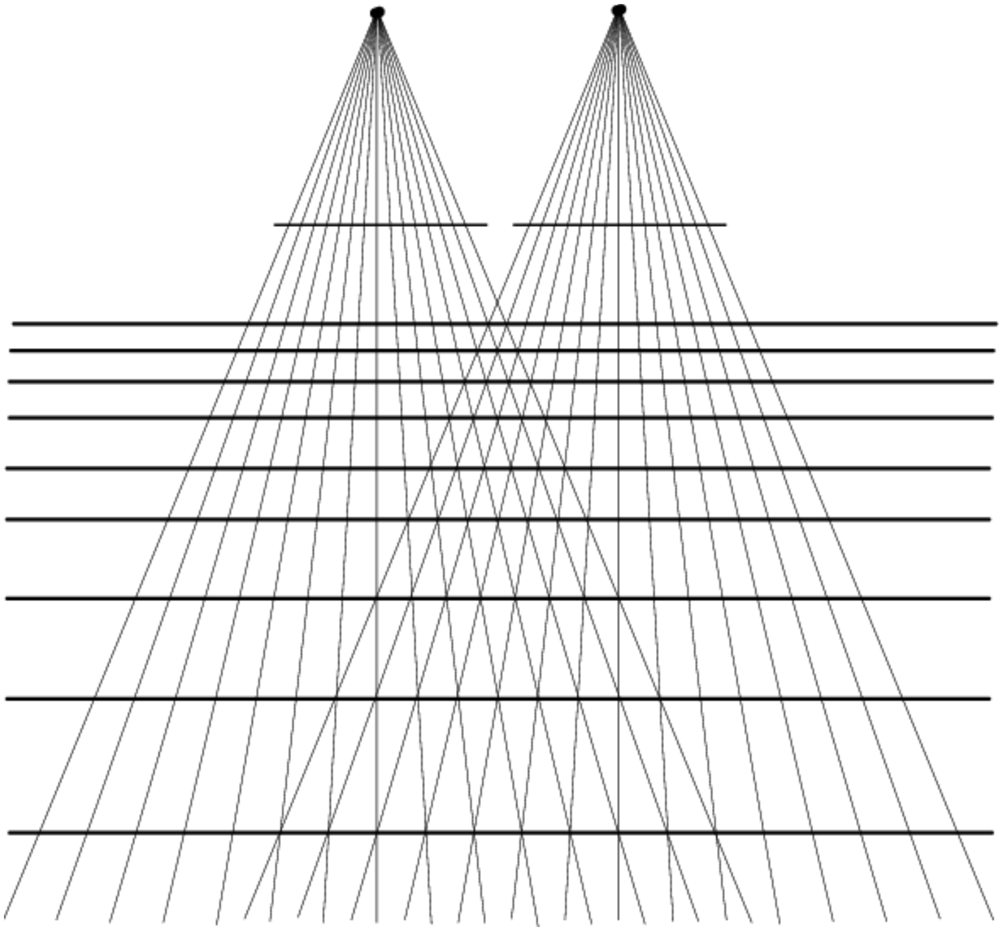
$$Z = bk_x\frac{f}{(x - x')}.$$

$(x - x')$ is the so-called *disparity*

Stereo is imprecise for far away objects,but increasing b and/or f can increase depth resolution

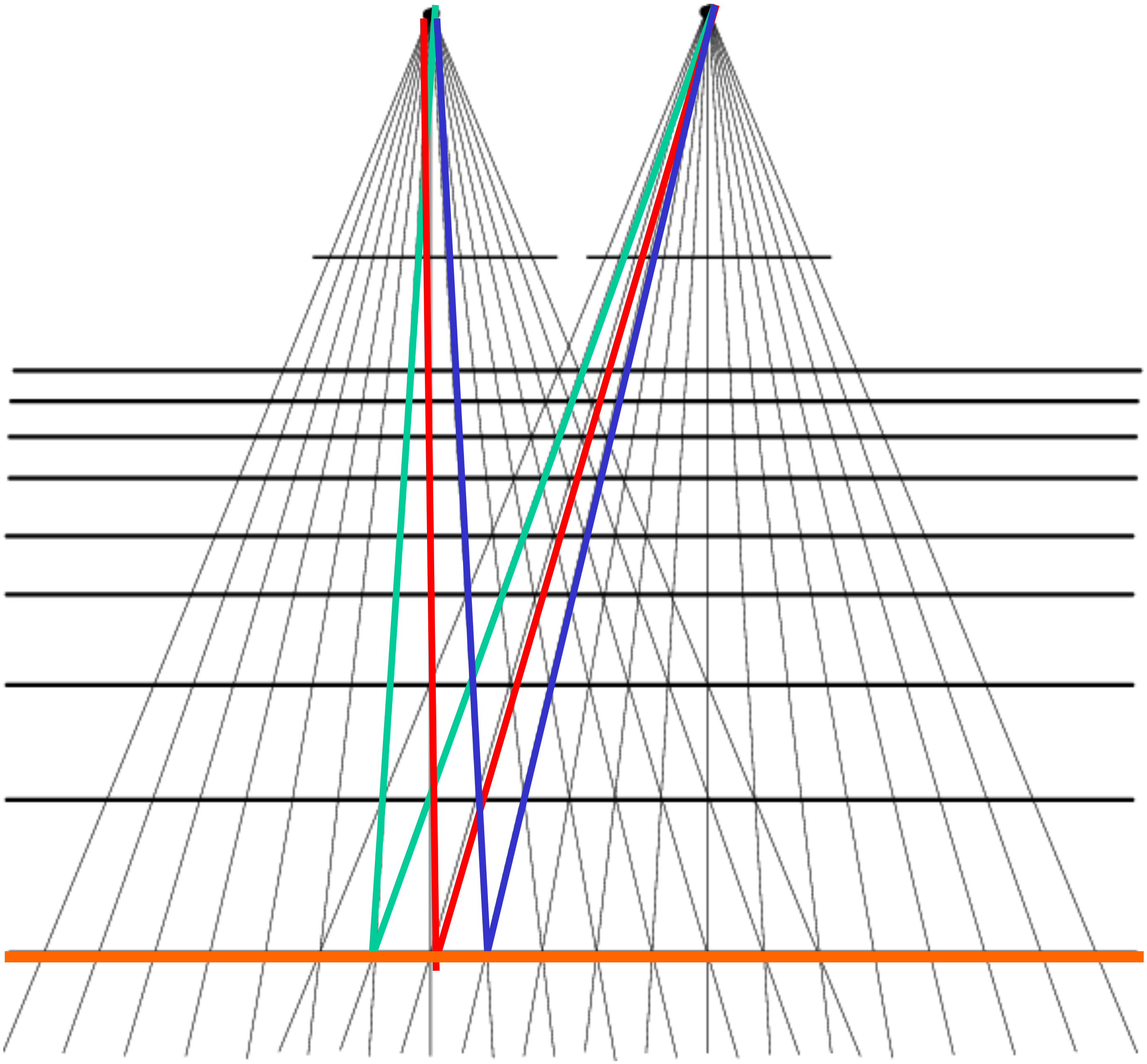
A simple stereo setup

Notice: for this simple setup, same disparity means same depth



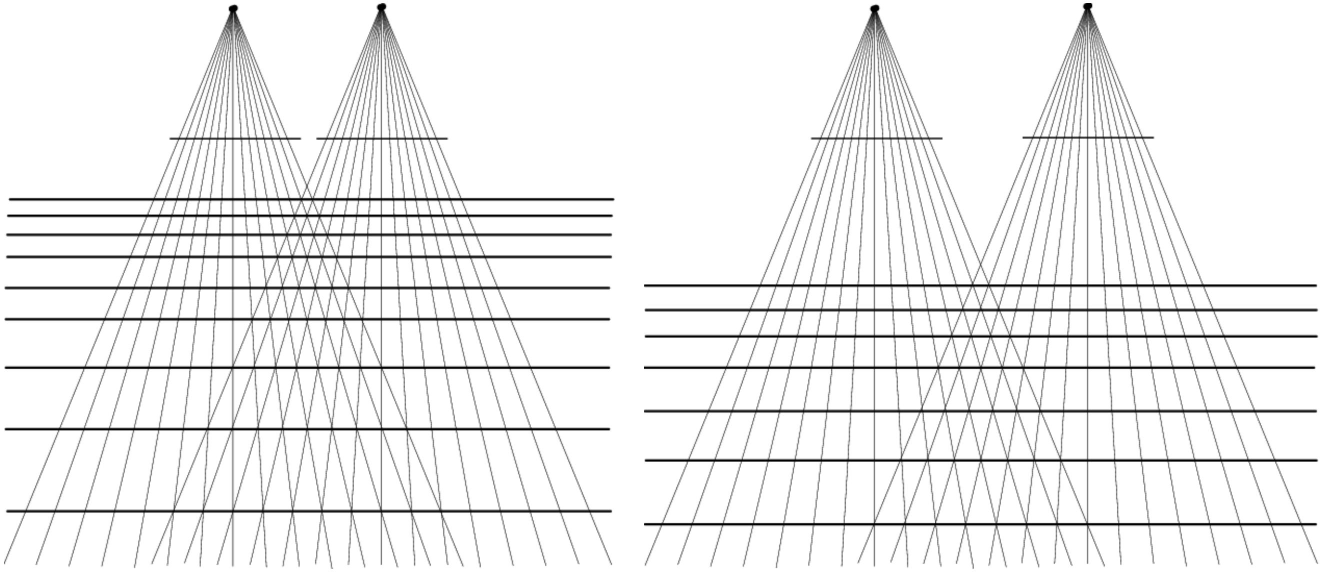
Computer Vision

same disparity means same depth



A simple stereo setup

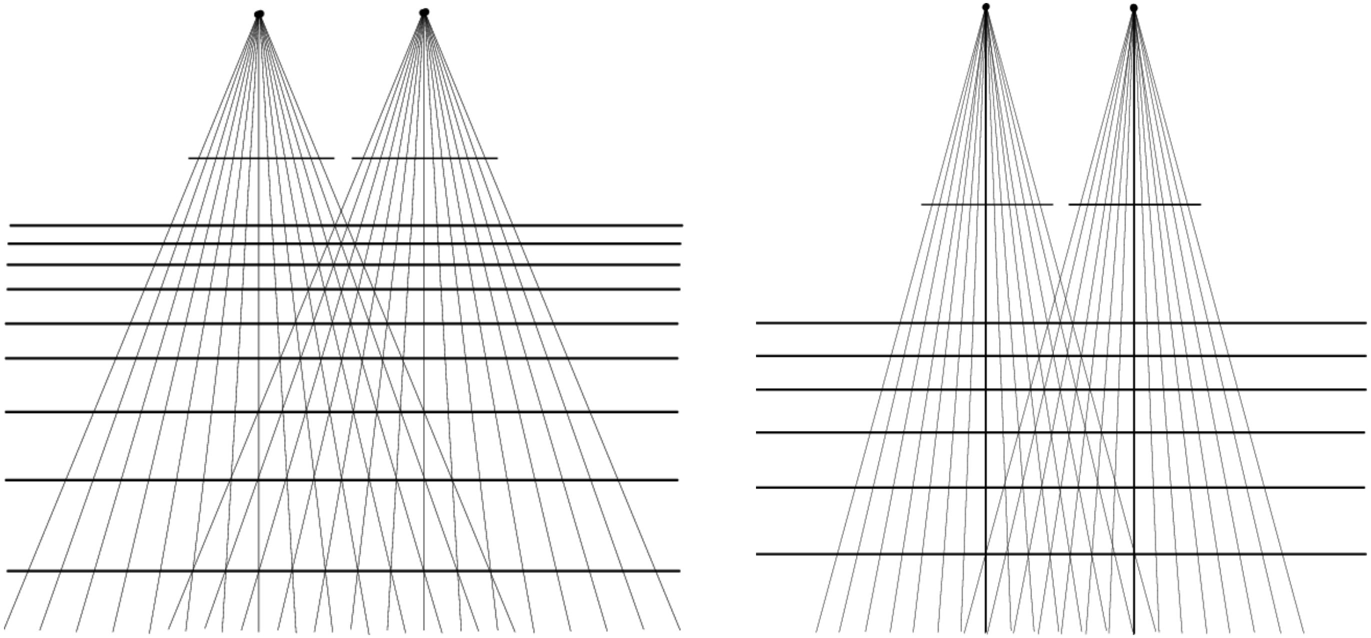
Increasing b increases depth resolution



one has to strike a balance with visibility...

A simple stereo setup

Increasing f increases depth resolution

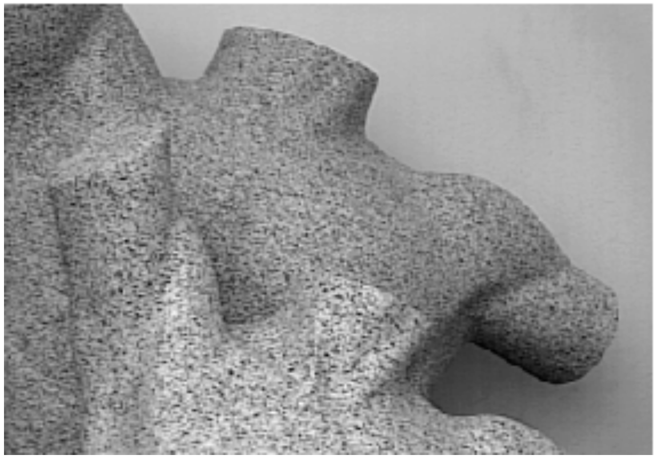


one has to strike a balance with visibility...

Remarks

- 1. increasing b and/or f increases depth resolution but reduces simultaneous visibility
- 2. iso-disparity loci are depth planes, not so for other configurations
- 3. human stereo vision only works up to ± 10 m
- 4. the real problem is finding correspondences

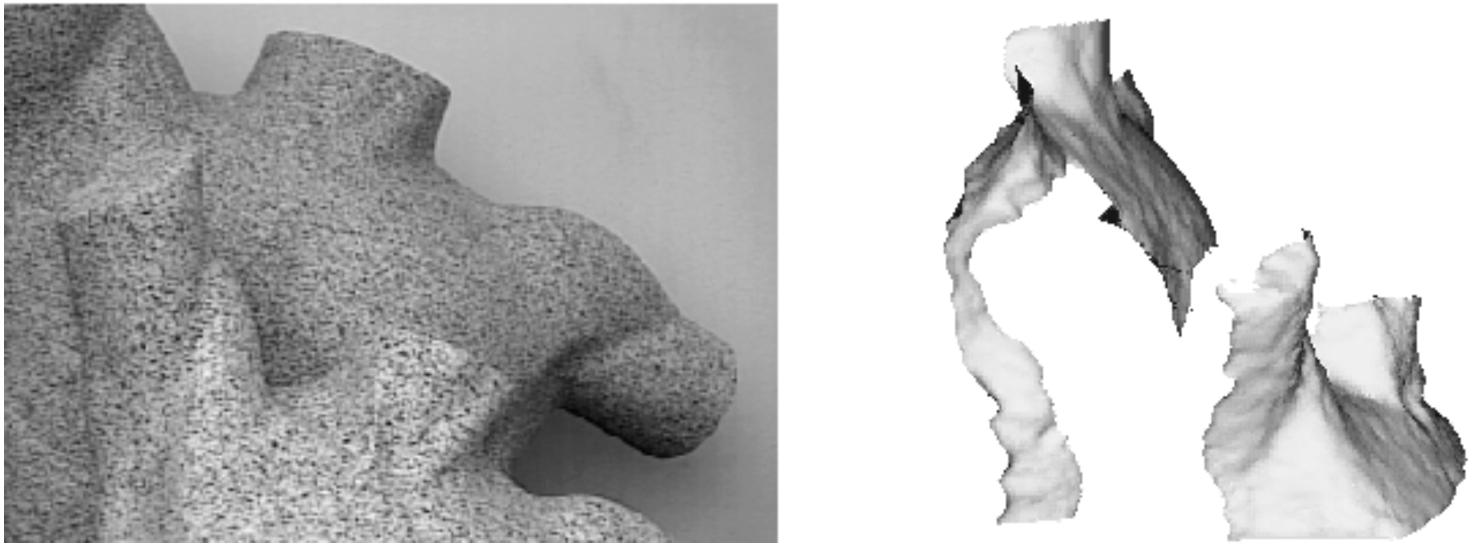
A simple stereo setup



The HARD problem is finding the *correspondences*

Notice : no reconstruction for the untextured back wall...

A simple stereo setup



The HARD problem is finding the *correspondences*

Notice : no reconstruction for the untextured back wall…

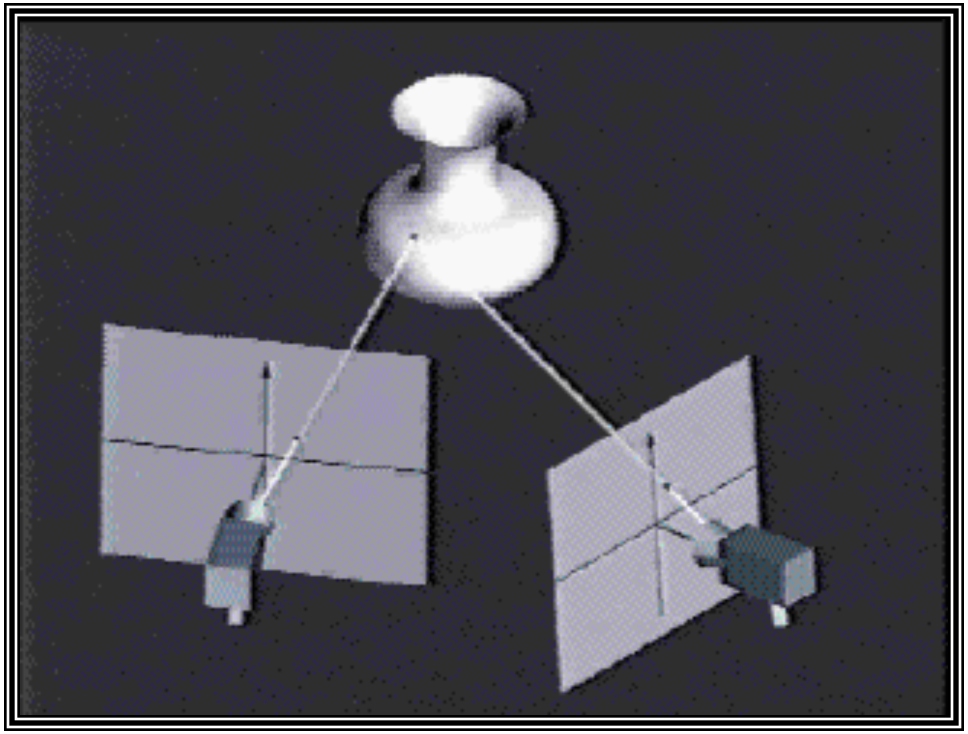
Computer
Vision

Sidmar

Stereo, the general setup

we start by the relation between the two projections of a point

in the second image the point must be along the projection of the viewing ray for the first camera :



Stereo, the general setup

We cast this constraint in mathematical expressions :

p and p' are the two images of P

$$\mu\, p = K\, R^t (P - C)$$

$$\rho' p' = K' R'^t (P - C')$$

w.r.t. world frame P is on the ray with equation

$P = C + \mu R K^{-1} p$ for some $\mu \in \mathbb{R}$

Stereo, the general setup

so, the ray is given by

$$P = C + \mu R K^{-1} p \quad \text{for some} \quad \mu \in \mathbb{R}$$

now we project it onto the second image
in general, points project as follows :

$$\rho' p' = K' R'^{t} (P - C')$$

and thus, filling in the ray's equation

$$\rho' p' = \mu K' R'^{t} R K^{-1} p + K' R'^{t} (C - C')$$

Stereo, the general setup

the projected ray was found to be

$$\rho' p' = \mu K' R'^t R K^{-1} p + K' R'^t (C - C')$$

the second term is the projection of the 1st camera's center, the so-called *epipole*

$$\rho'_e e' = K' R'^t (C - C')$$

the first term is the projection of the ray's point at infinity, the so-called *vanishing point*

finally, adopting the simplifying notation

$$A = \frac{1}{\rho'_e} K' R'^t R K^{-1}$$

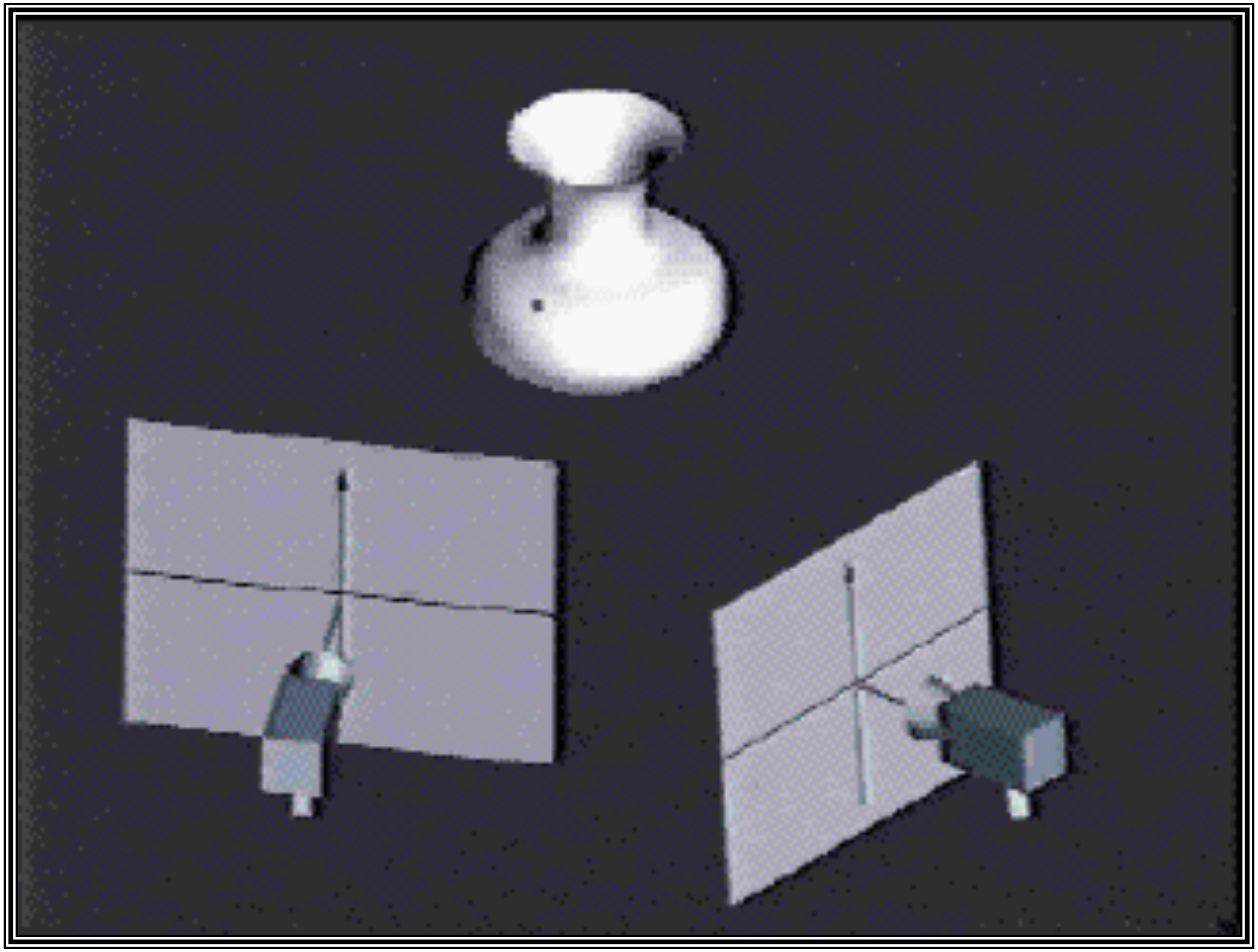
$$\rho' p' = \rho'_e (\mu A p + e')$$

A is the *infinity homography*

➔

Stereo, the general setup

note that the epipole lies on all the epipolar lines



Stereo, the general setup

$$\rho' p' = \rho'_e(\mu A p + e')$$

Stereo, the general setup

$$\rho' p' = \rho'_e(\mu A p + e')$$

expresses that p' lies on the line l' through the epipole e' and the vanishing point Ap of the ray of sight of p (in the 2nd image)

→

Stereo, the general setup

$$\rho' p' = \rho'_e(\mu A p + e')$$

the epipolar constraint (epipolar line)

we can rewrite this constraint as

$$|p' e' A p| = p'^t(e' \times A p) = 0$$

Stereo, the general setup

$$|p'e'Ap| = p'^t(e' \times Ap) = 0$$

can be written, given

$$[e']_\times = \begin{pmatrix} 0 & -e'_3 & e'_2 \\ e'_3 & 0 & -e'_1 \\ -e'_2 & e'_1 & 0 \end{pmatrix}$$

as

$$|p'e'Ap| = p'^t[e']_\times Ap$$

$F = [e']_\times A$ is the *fundamental matrix*

F is a 3x3 matrix, but has rank 2

Stereo, the general setup

$$p'^t [e']_\times A p = 0 \quad \rightarrow \quad \boxed{p'^t \; F \; p = 0}$$

The 3-vector $p'^t F$ contains the line coordinates of the epipolar line of p' (i.e. a line in the 1st image)

The 3-vector $F\,p$ contains the line coordinates of the epipolar line of p (i.e. a line in the 2nd image)

Hence, the epipolar matrix works in both directions

Stereo, the general setup

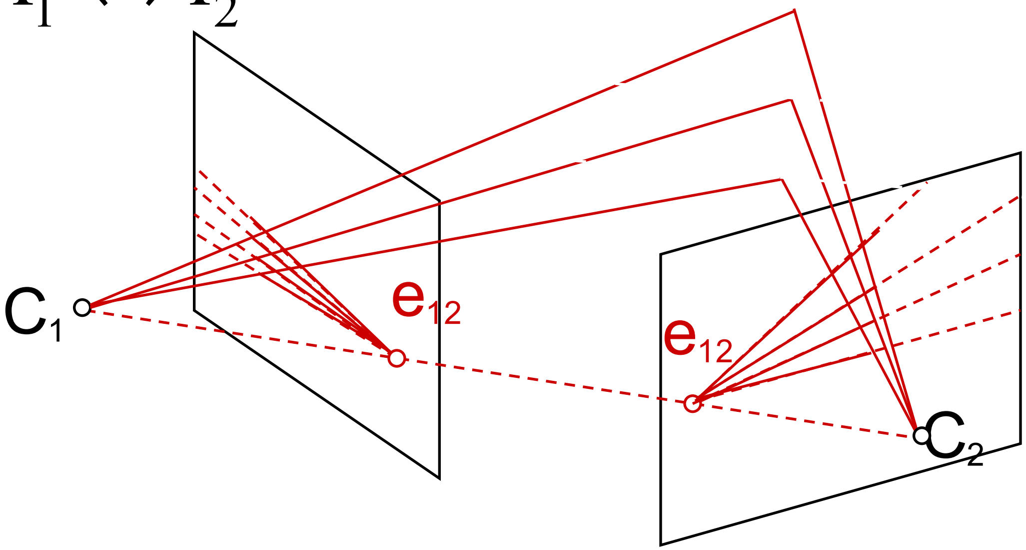
Andrea Fusiello, CVonline

Epipolar geometry cont’d

Epipolar geometry cont'd

- Epipolar lines are in mutual correspondence

$$l_1 \leftrightarrow l_2$$

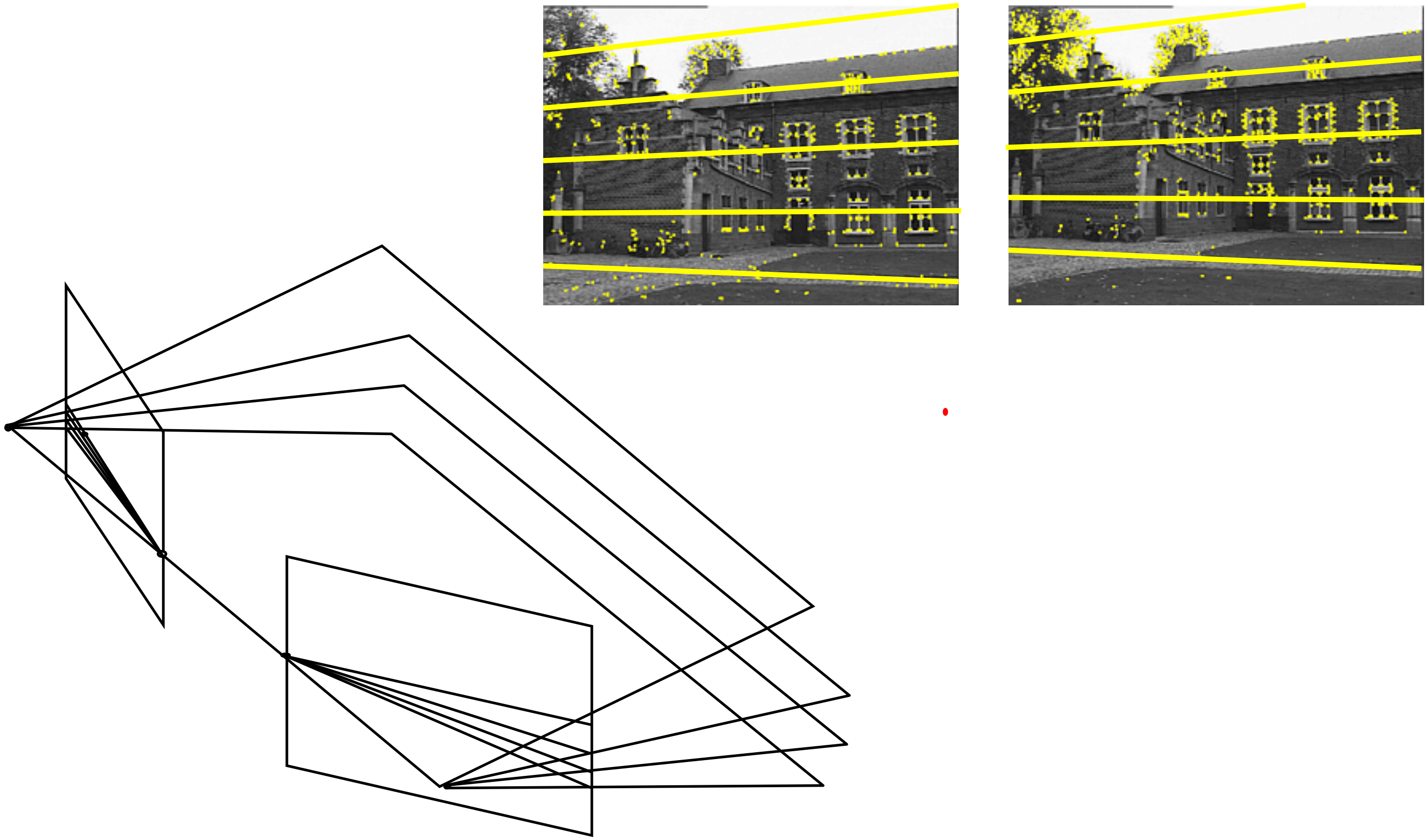


- allows to separate matching problem:

matching pts on an epipolar line to pts on the corresponding epipolar line

Exploiting epipolar geometry

Separate 2D correspondence search problem to 1D search problem by using two view geometry



Epipolar geometry cont’d

Stereo, the general setup

- ❑ one point yields one equation $p'^t F\ p = 0$ that is linear in the entries of the fundamental matrix F
  so, we can actually obtain F without any prior knowledge about camera settings if we have sufficient pairs of corresponding points !!

- ❑ F can be computed *linearly* from 8 pairs of corresponding points,
  i.e. already from 8 `correspondences'
  (not 9, as this is a homogeneous system and one coefficient can be fixed to value 1 to fix the scale !)

- ❑ F being rank 2 yields an additional, but non-linear constraint. Thus, 7 correspondences suffice to *non-linearly* solve for F

Stereo, the general setup

Remarks :

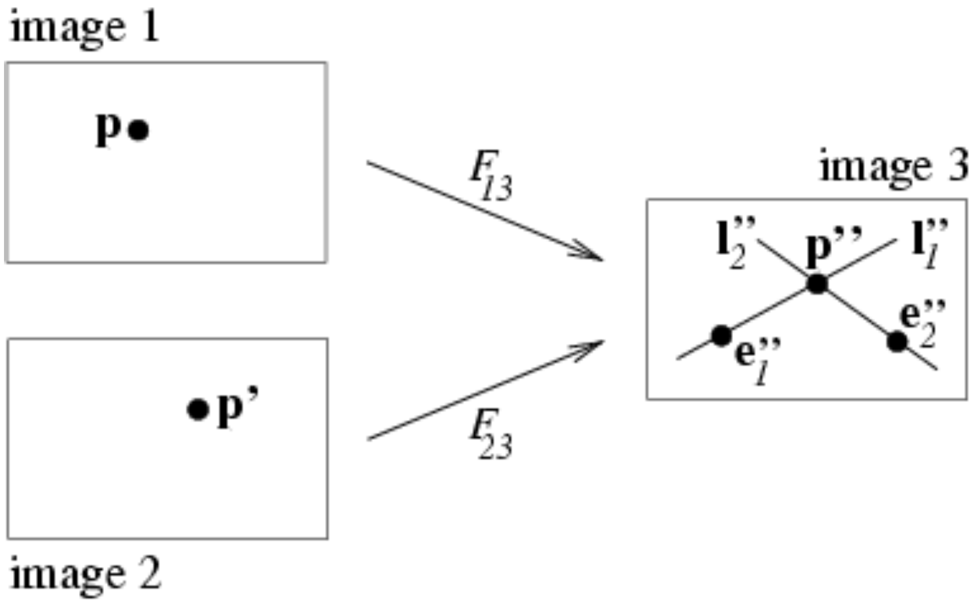
- Of course, in practice one wants to use as many Correspondences as available, e.g. for obtaining a least-squares solution, based on the linear system, followed by a step to impose rank 2.

- Often, F is found through a procedure called RANSAC (RANdom Sample Consensus). It starts from a randomly drawn subset of correspondences of minimal size (e.g. 8), and then keeps on drawing until a subset is found that yields an F so that many correspondences are seen to obey the epipolar constraint. RANSAC is good to fend off against correspondences that are wrong (`outliers')

➔

Relations between 3 views

one could use more than 2 images, e.g. 3
suppose P projects to p,p', and p''
p'' is found at the intersection of epipolar lines :



fails when the epipolar lines coincide

⇒ *trifocal constraints*

Computer Vision

Correspondence problem : constraints

Reducing the search space :

- 1. Points on the epipolar line
- 2. Min. and max. depth ⇒ line segment
- 3. Preservation of order
- 4. Smoothness of the disparity field

Correspondence problem : methods

1. correlation
    - deformations…
    - small window ⇒ noise!
    - large window ⇒ bad localisation
2. feature-based
    - mainly edges and corners
    - sparse depth image
3. regularisation methods

Stereo, the general setup

3D reconstruction

$$P = C + \mu R K^{-1} p$$

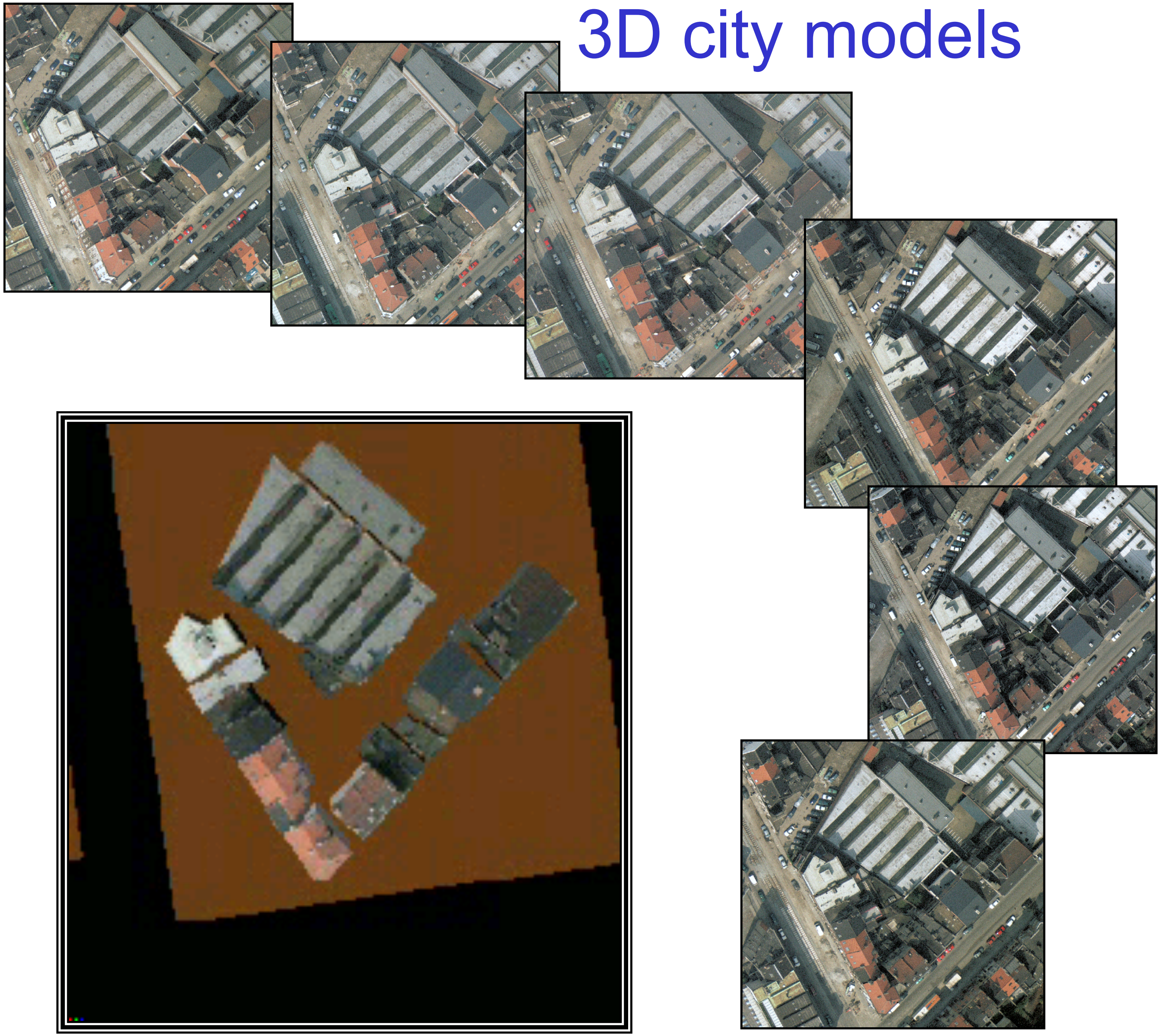
$$P = C' + \mu' R' K'^{-1} p'$$

Yields 6 equations in 5 unknowns X,Y, Z and μ, μ’

However, due to noise and errors, the rays may not intersect!

⇒ e.g. use the middle where the rays come closest

3D city models



3D city models – ground level

Mobile mapping example – for measuring

3D city models – ground level

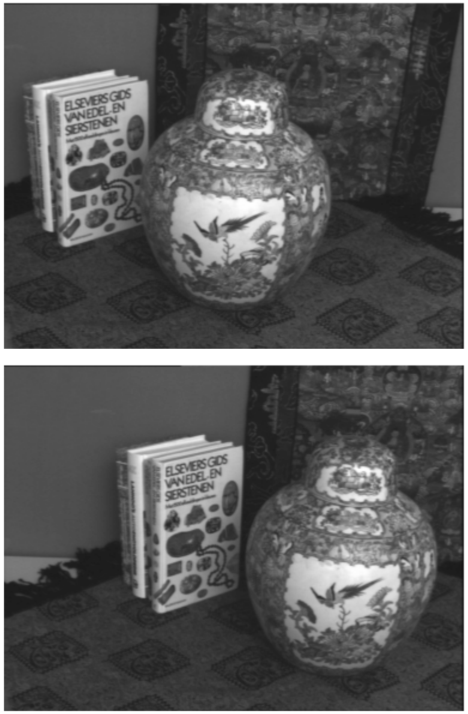
Can also be turned into 3D for visualisation, but one needs to stay close to the camera viewpoints.

The example shown is of Quebec

3D city models – ground level

Uncalibrated reconstruction

From 2 views...



If the camera translates...

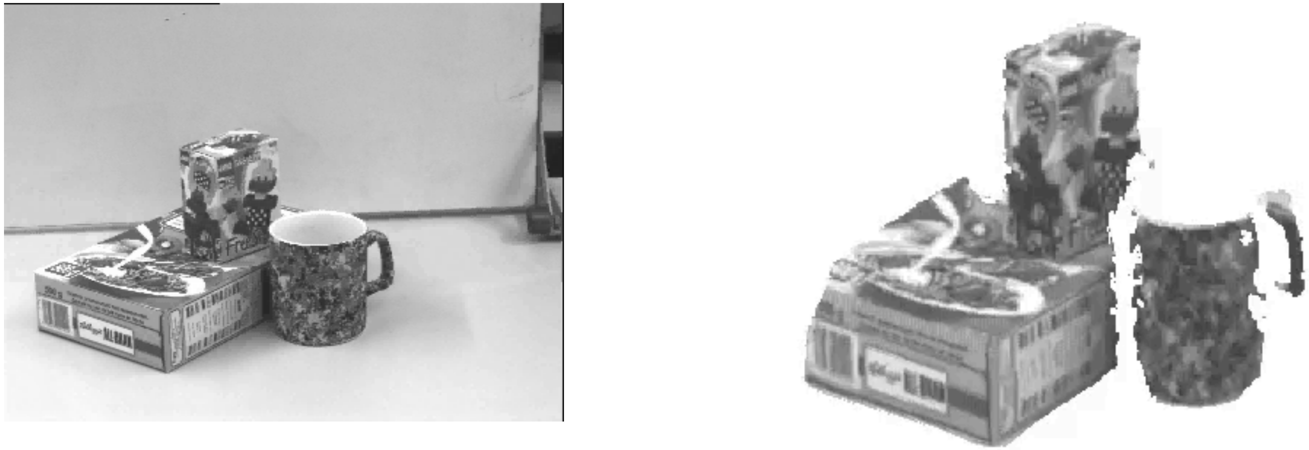
An affine reconstruction can be made

A projective reconstruction is always possible

(if no pure rot.)

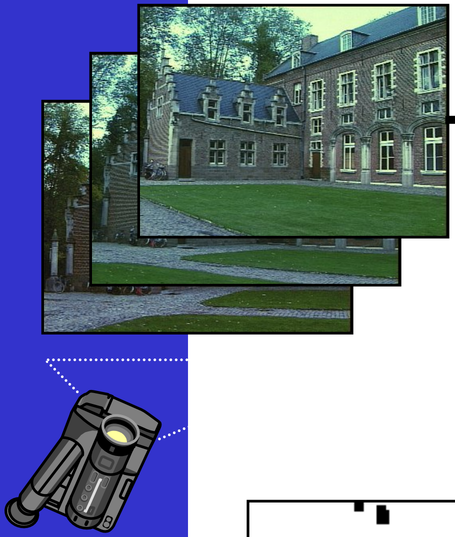
Uncalibrated reconstruction

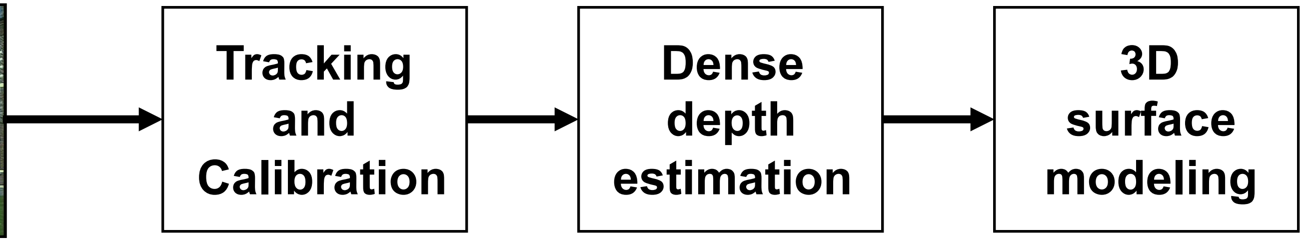
From 3 general views
taken with the same camera parameters...



A metric reconstruction is possible

Uncalibrated reconstruction

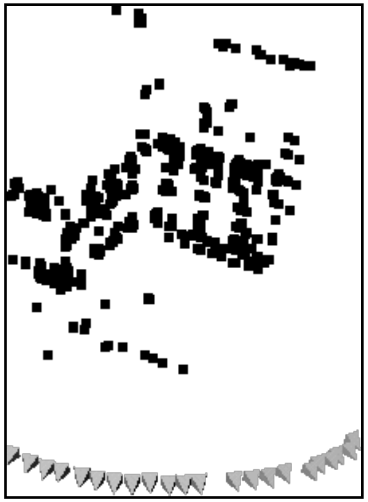




Tracking and Calibration

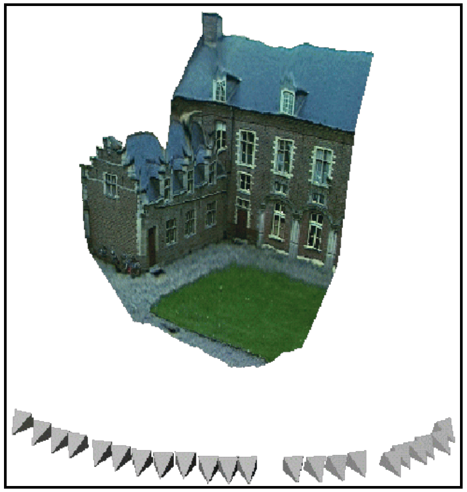
Dense depth estimation

3D surface modeling



Points and cameras

Depth map



3D models

Uncalibrated reconstruction

Uncalibrated reconstruction - example

Univ. of Leuven

Shape-from-stills

Input Images

shots taken with Canon EOS D60

(Resolution: 6,3 Megapixel)

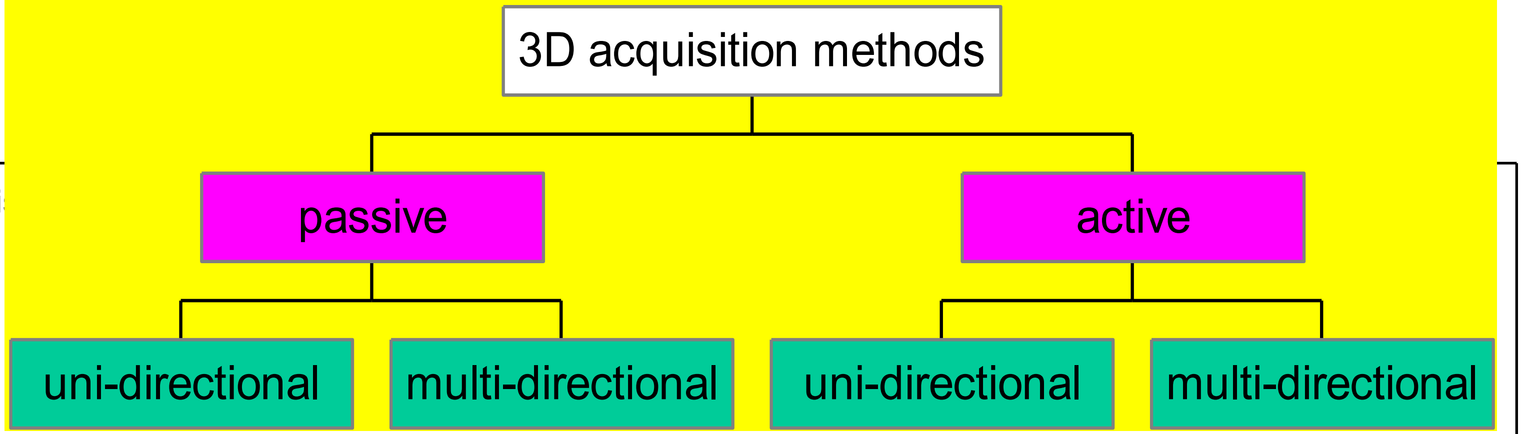
copyright Eyetronics

Shape-from-stills

www.arc3d.be

Webservice,
free for non-commercial use

3D acquisition taxonomy



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Stereo

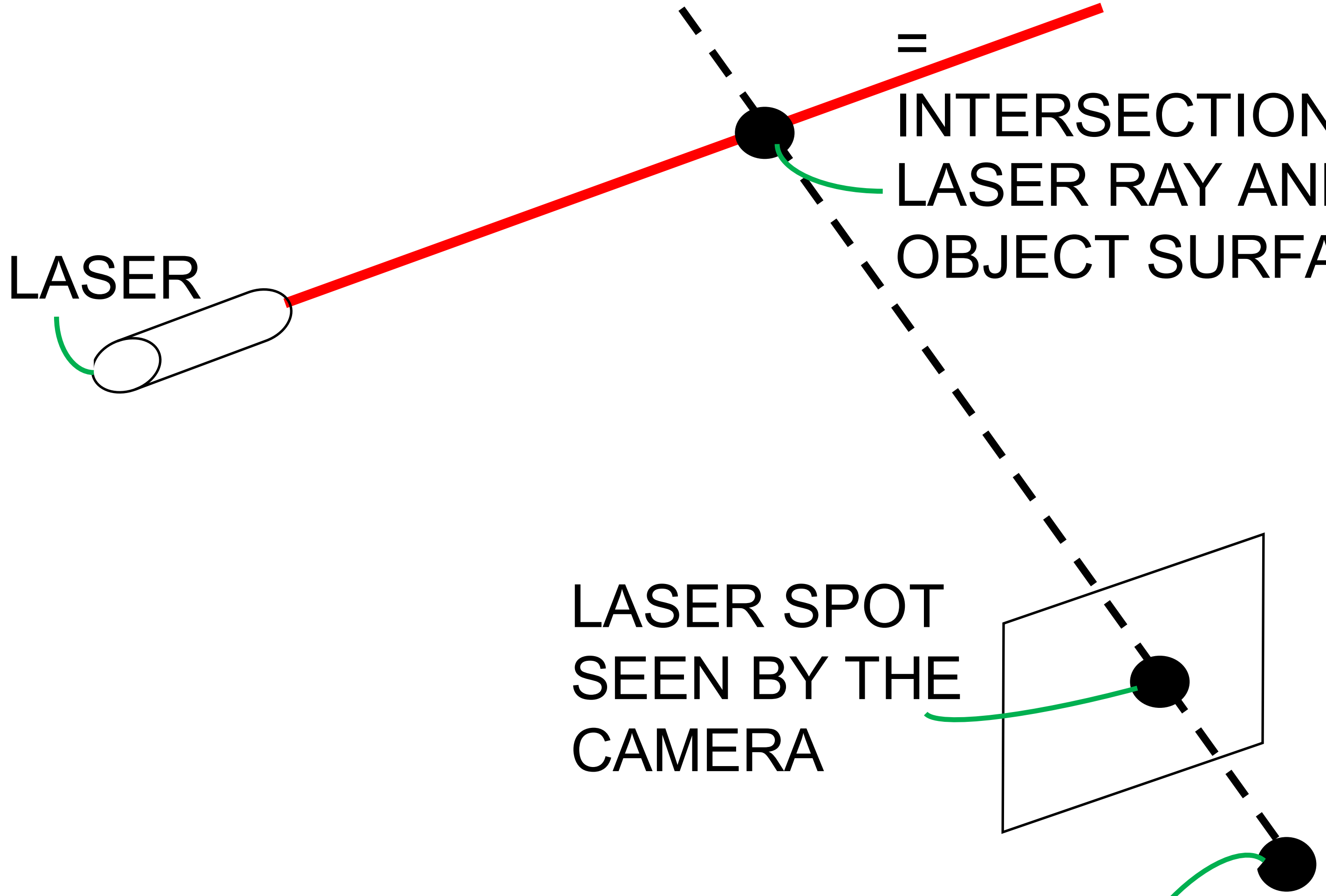
Time-of-flight

Line scanning

Structured light

Photom. stereo

Active triangulation



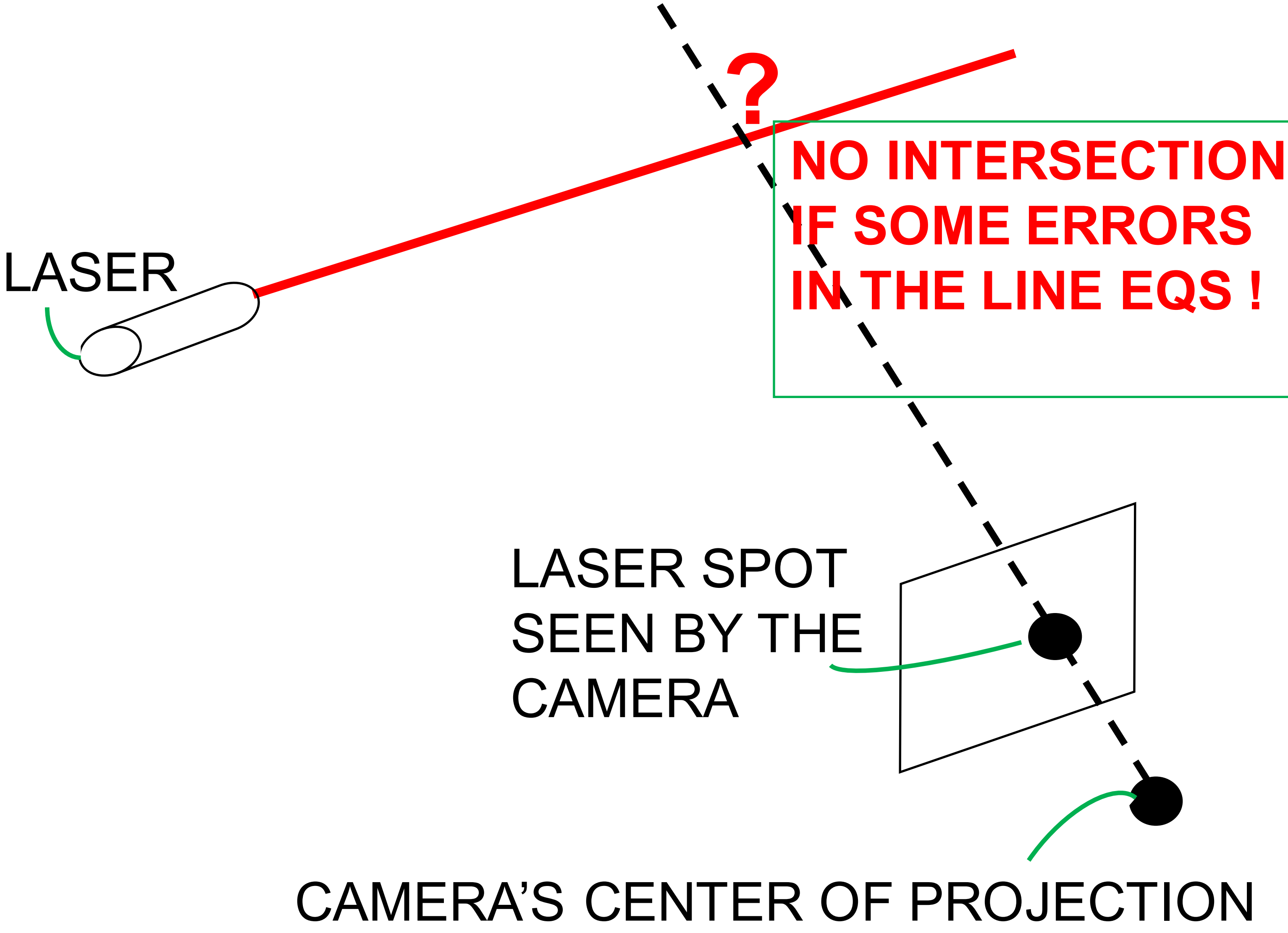
INTERSECTION
LASER RAY AND
VIEWING RAY
=
INTERSECTION
LASER RAY AND
OBJECT SURFACE

LASER

LASER SPOT
SEEN BY THE
CAMERA

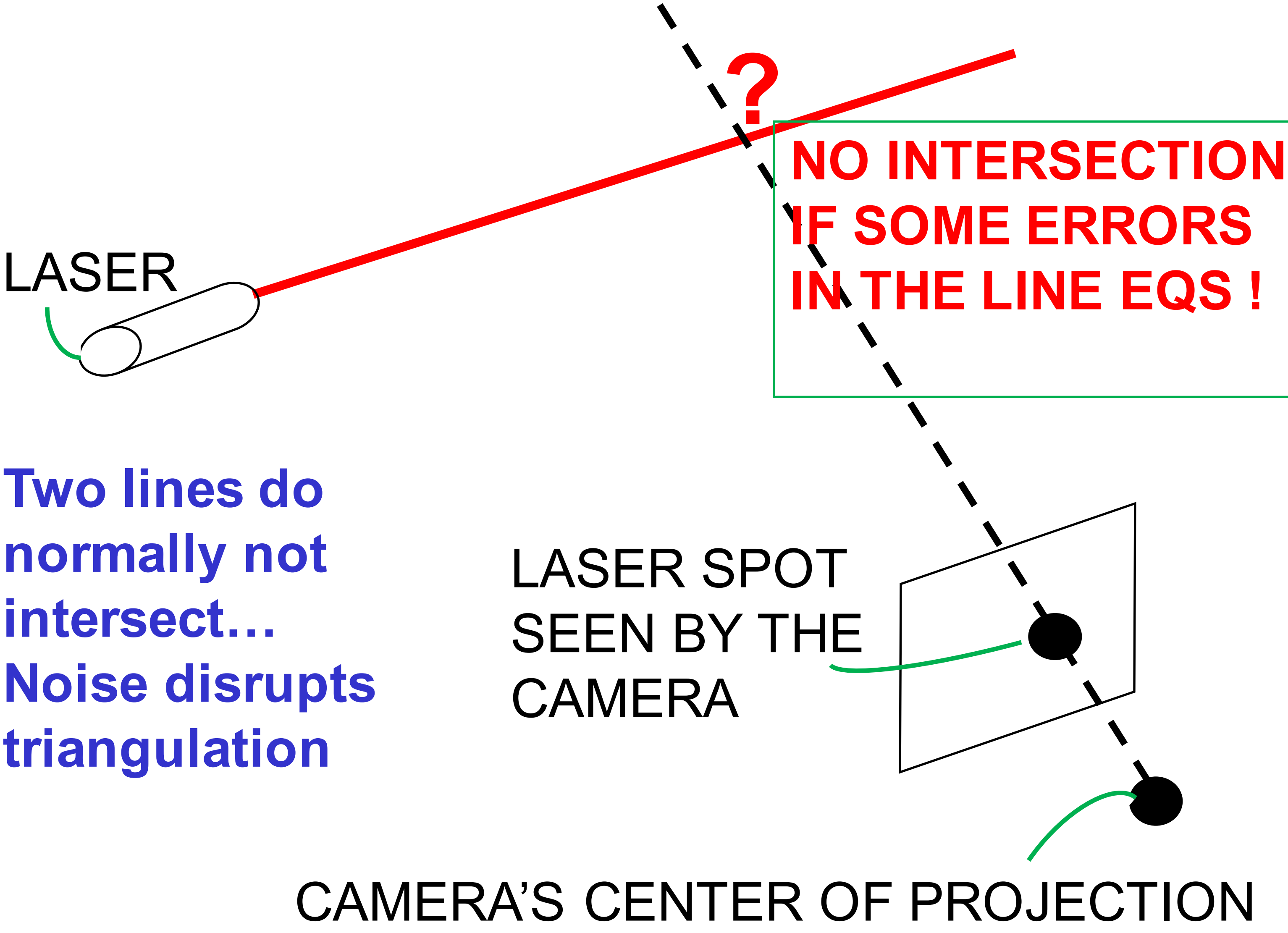
CAMERA'S CENTER OF PROJECTION

Active triangulation



NO INTERSECTION IF SOME ERRORS IN THE LINE EQS !

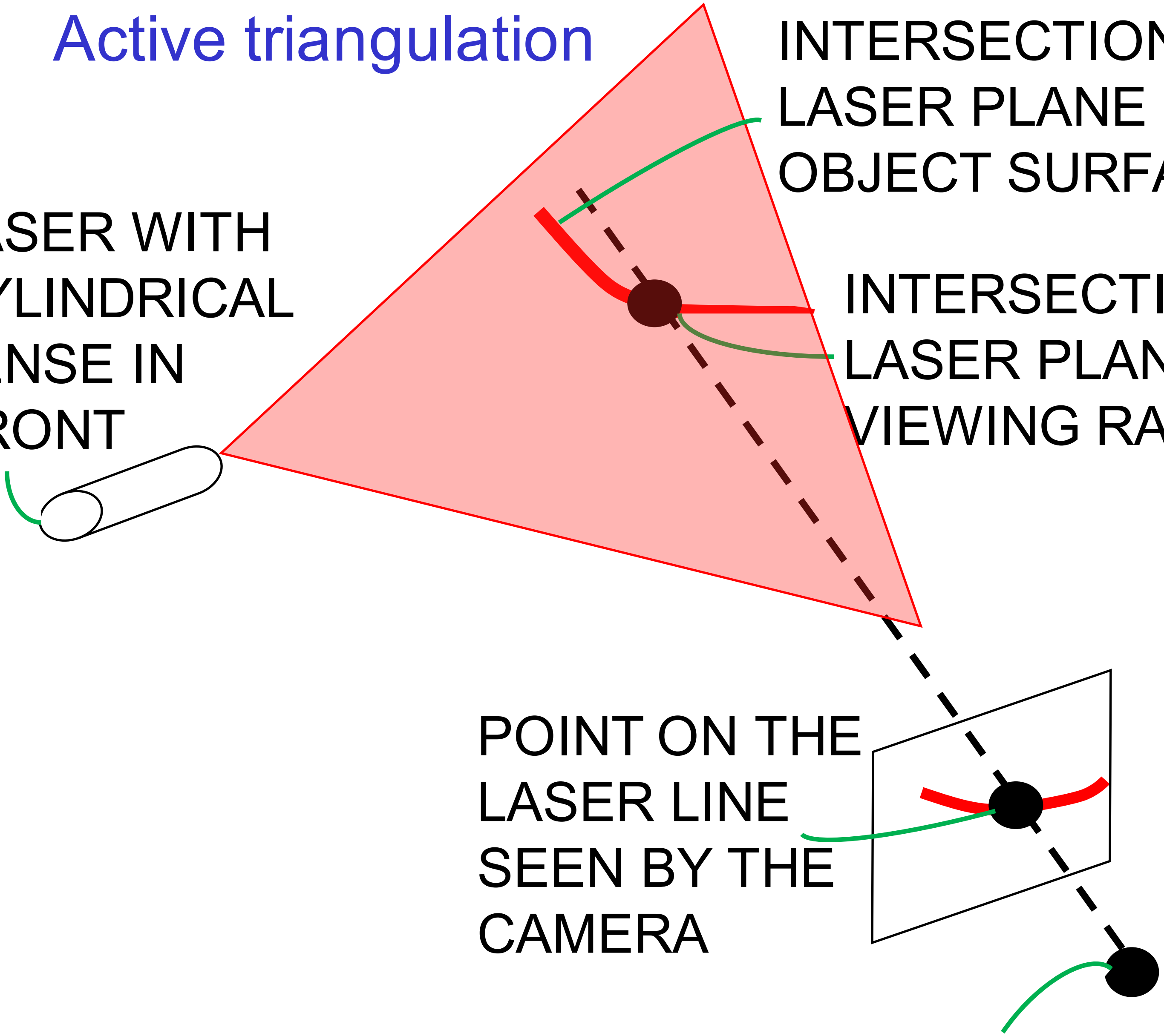
Active triangulation



**NO INTERSECTION
IF SOME ERRORS
IN THE LINE EQS !**

**Two lines do normally not intersect…
Noise disrupts triangulation**

Active triangulation



INTERSECTION LASER PLANE & OBJECT SURFACE

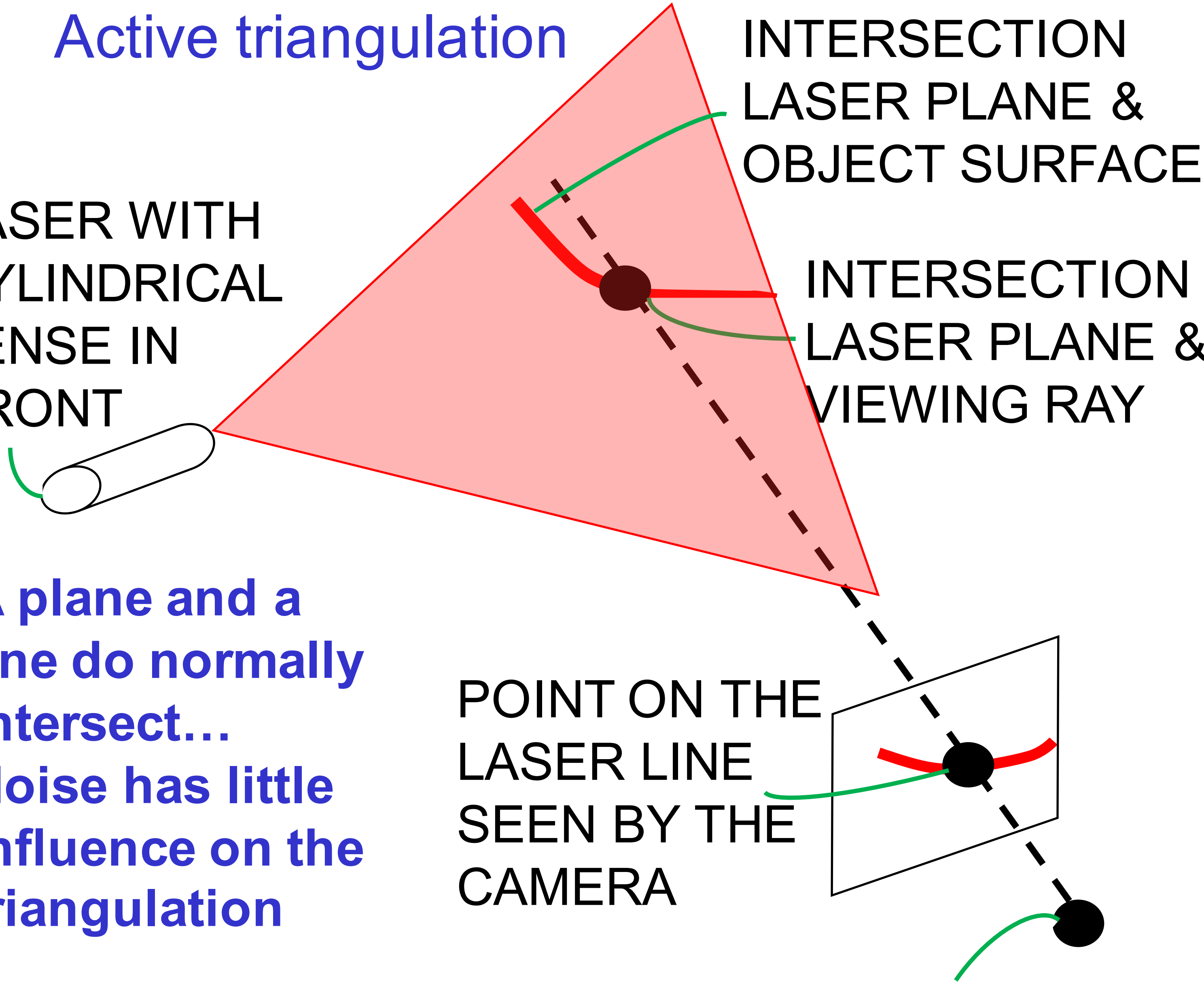
LASER WITH CYLINDRICAL LENSE IN FRONT

INTERSECTION LASER PLANE & VIEWING RAY

POINT ON THE LASER LINE SEEN BY THE CAMERA

CAMERA’S CENTER OF PROJECTION

Active triangulation



INTERSECTION LASER PLANE & OBJECT SURFACE

LASER WITH CYLINDRICAL LENSE IN FRONT

INTERSECTION LASER PLANE & VIEWING RAY

POINT ON THE LASER LINE SEEN BY THE CAMERA

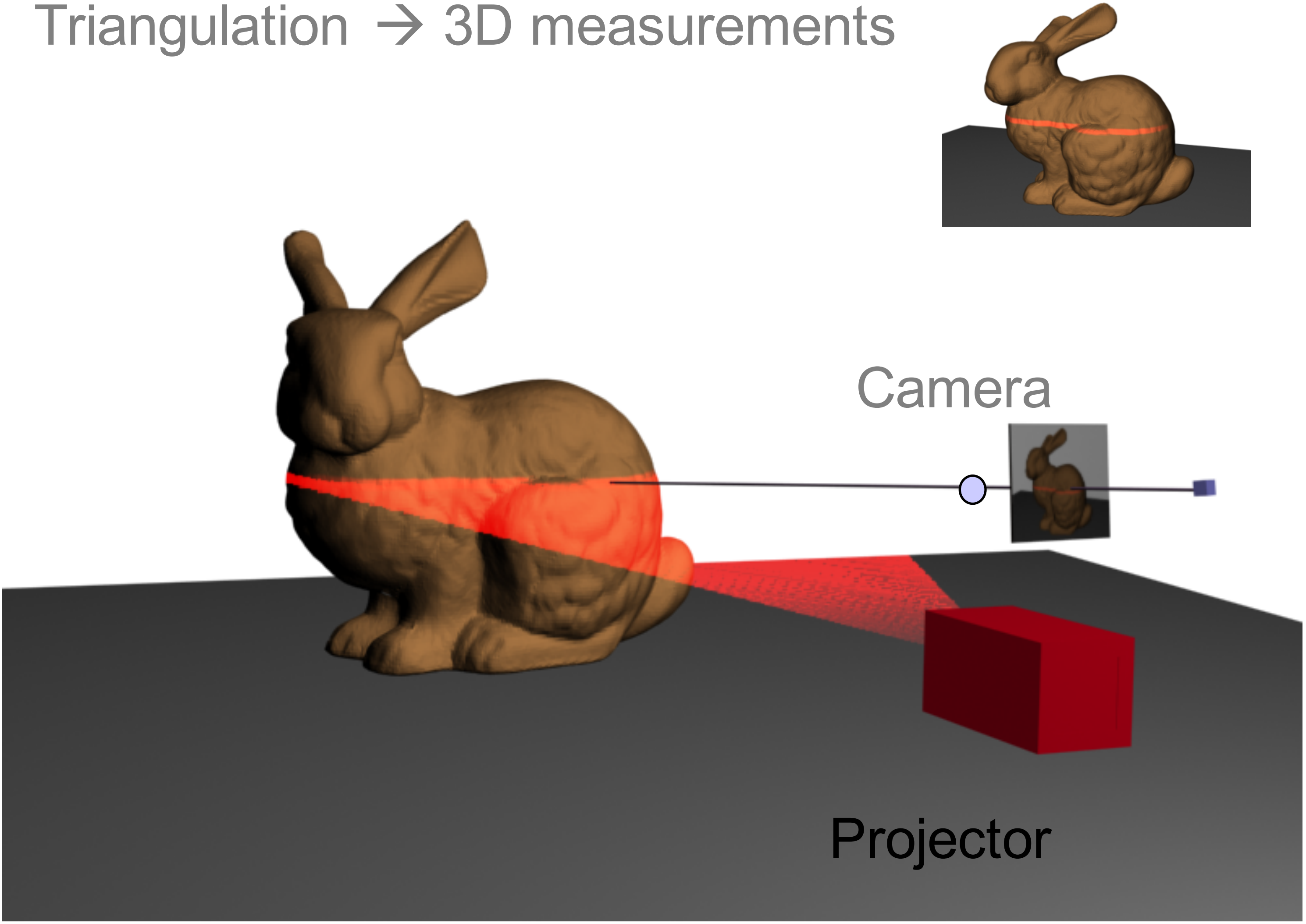
CAMERA'S CENTER OF PROJECTION

A plane and a line do normally intersect…
Noise has little Influence on the triangulation

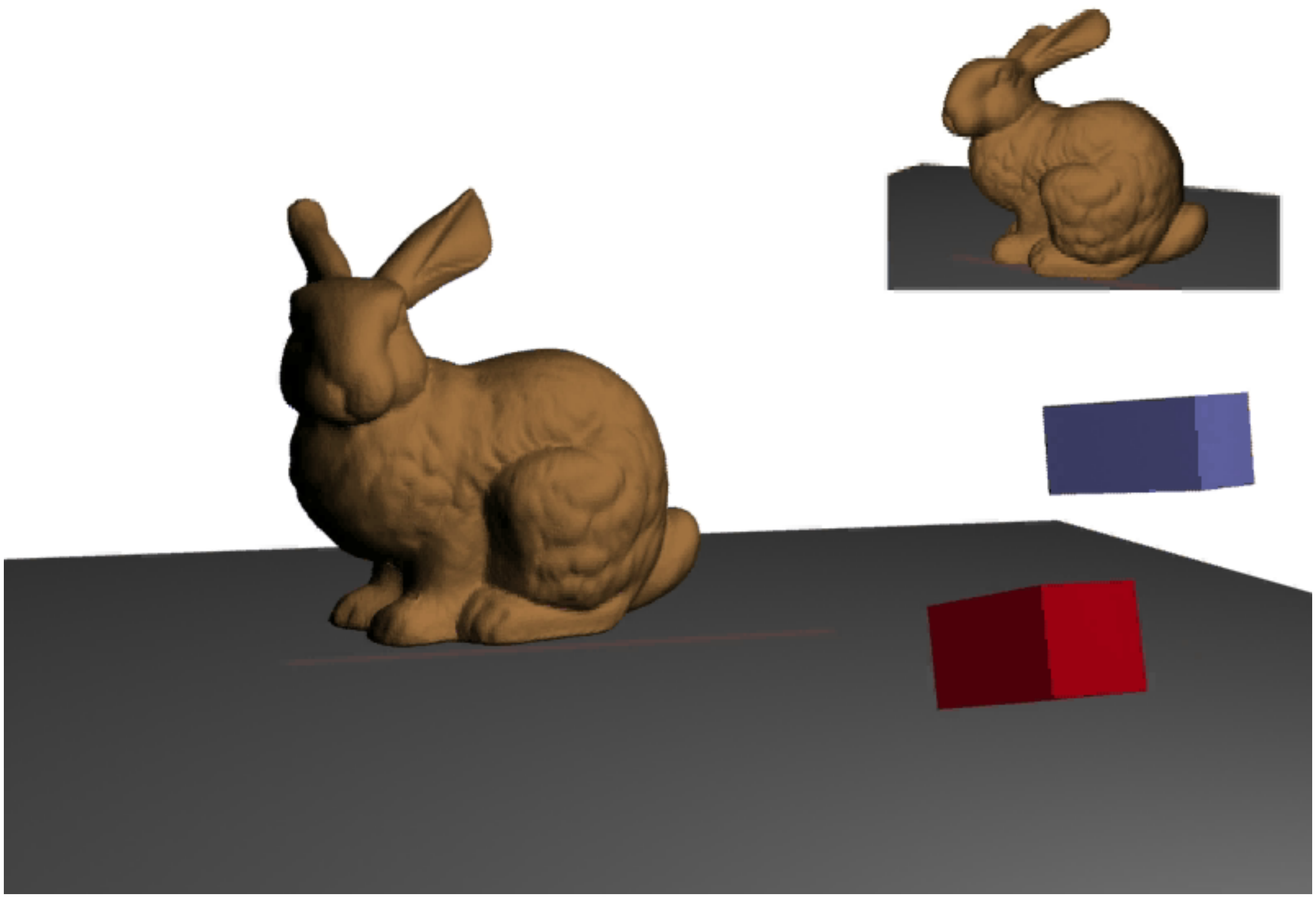
Active triangulation

Active triangulation

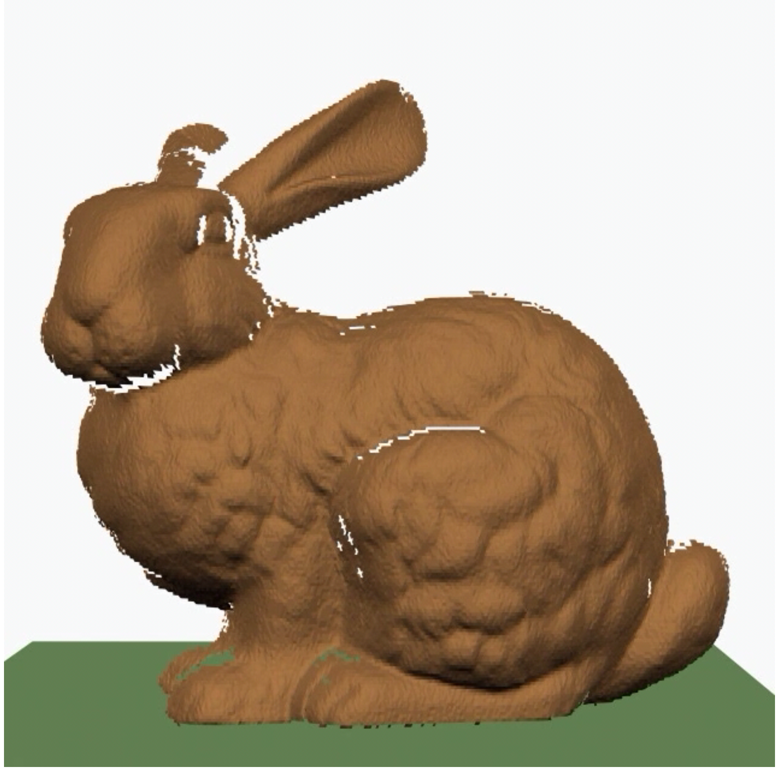
Triangulation → 3D measurements

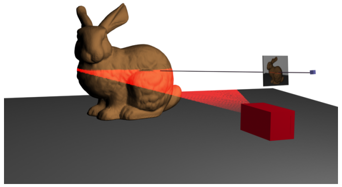


Active triangulation



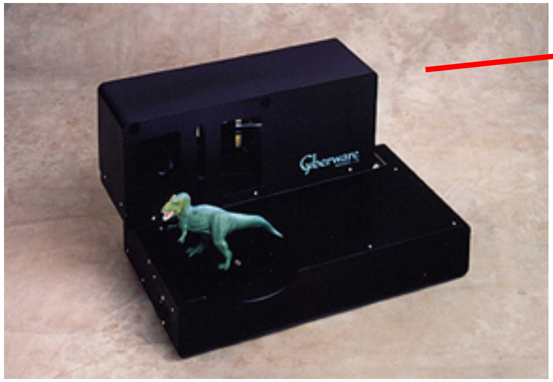
Active triangulation





Active triangulation

Example 1 Cyberware laser scanners



Desktop model for small objects

Medium-sized objects

Body scanner

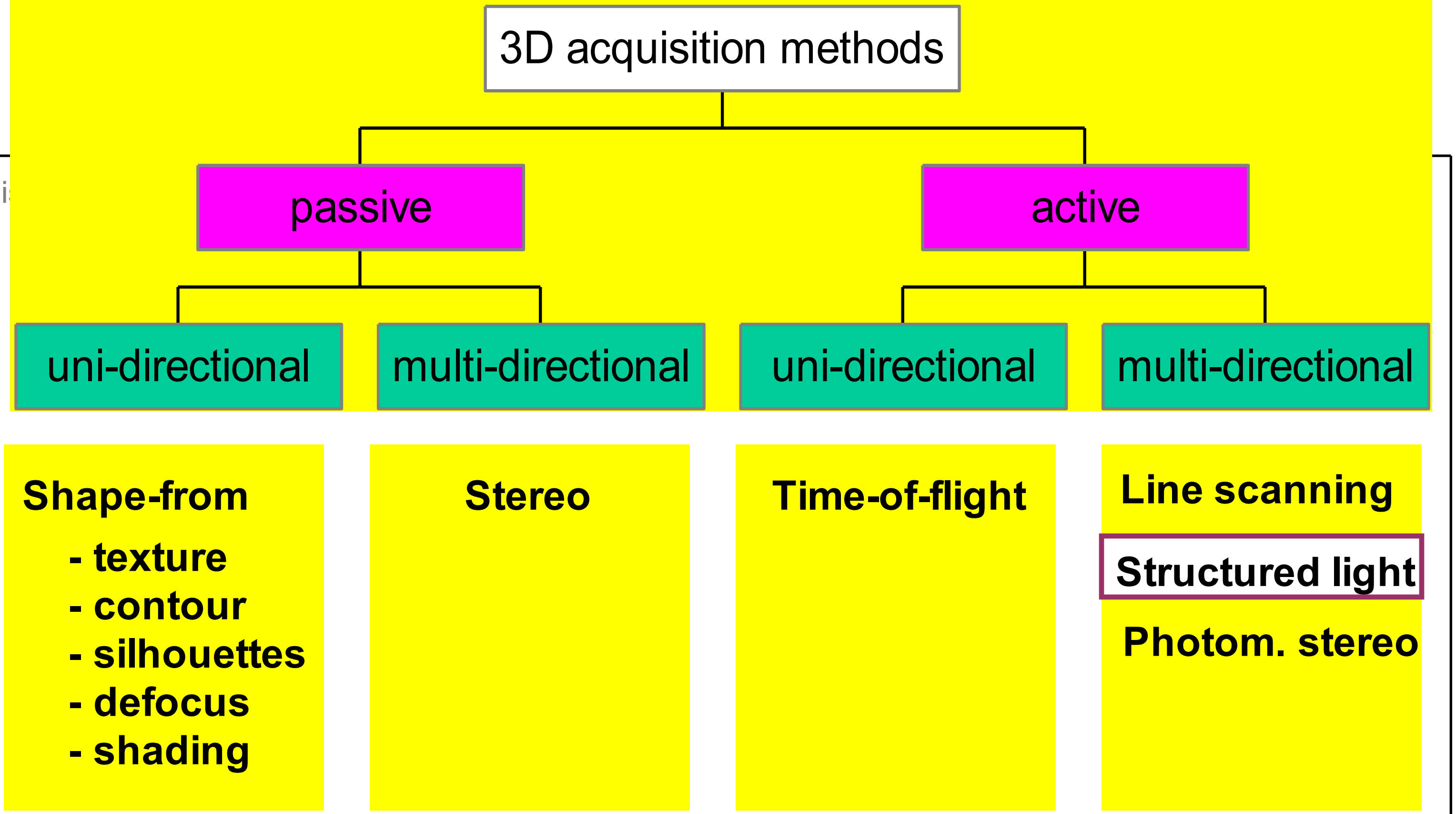
Head scanner

Active triangulation

Example 2 Minolta

Portable desktop model

3D acquisition taxonomy



3D acquisition methods

- passive
  - uni-directional
    - **Shape-from**
      - **- texture**
      - **- contour**
      - **- silhouettes**
      - **- defocus**
      - **- shading**
  - multi-directional
    - **Stereo**
- active
  - uni-directional
    - **Time-of-flight**
  - multi-directional
    - **Line scanning**
    - **Structured light**
    - **Photom. stereo**

Structured light

patterns of a special shape are projected onto the scene

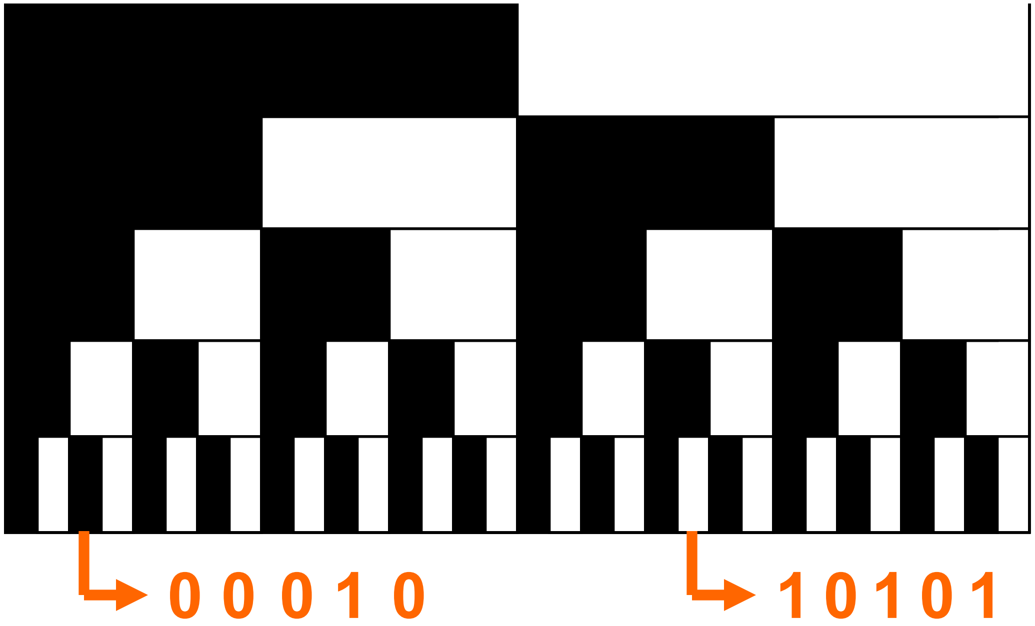
deformations of the patterns yield information on the shape

Focus is on combining a good resolution with a minimum number of pattern projections

Serial binary patterns

A sequence of patterns with increasingly fine subdivisions

Yields 2^n identifiable lines for only n patterns



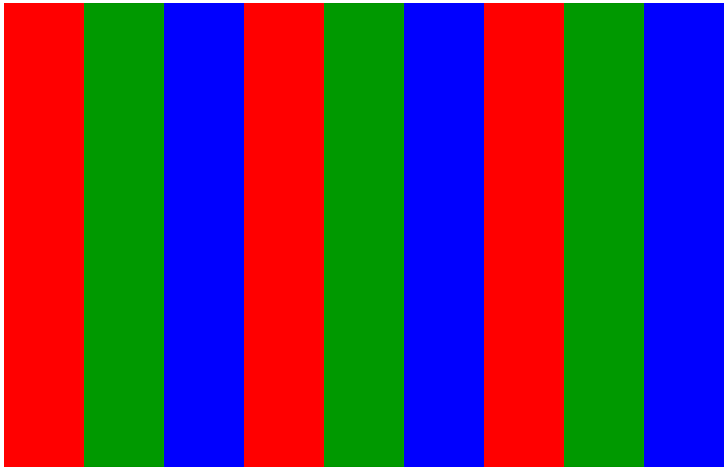
Reducing the nmb of projections: colour

Binary patterns

Yields 2^n identifiable lines for only n patterns

Using colours, e.g. 3,

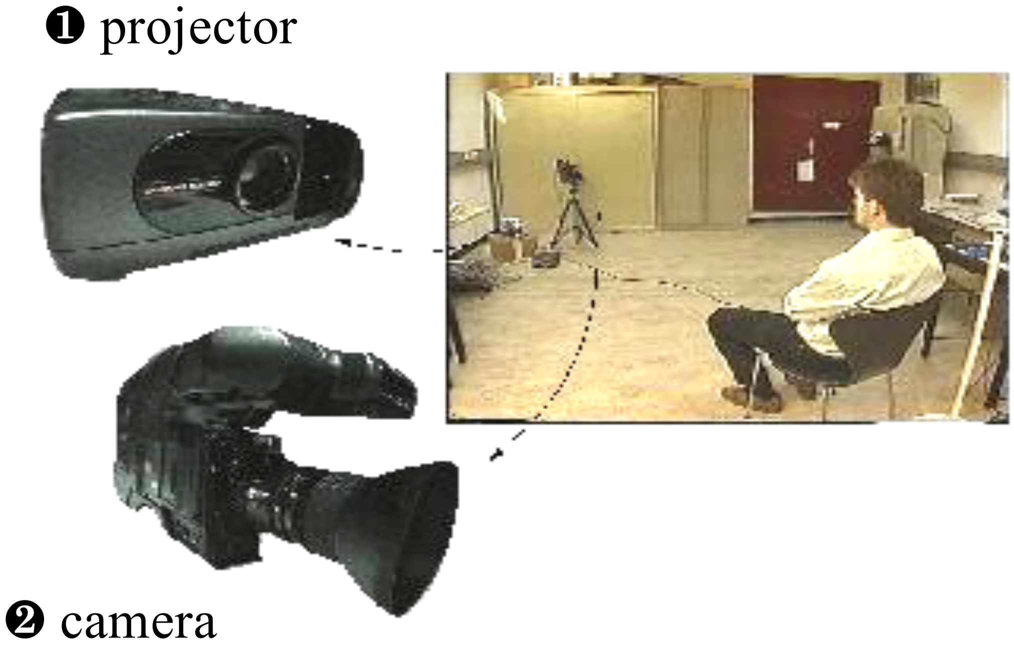
Yields 3^n identifiable lines for only n patterns



Interference from object colours...

One-shot implementation

3D from a single frame – KULeuven ‘96:

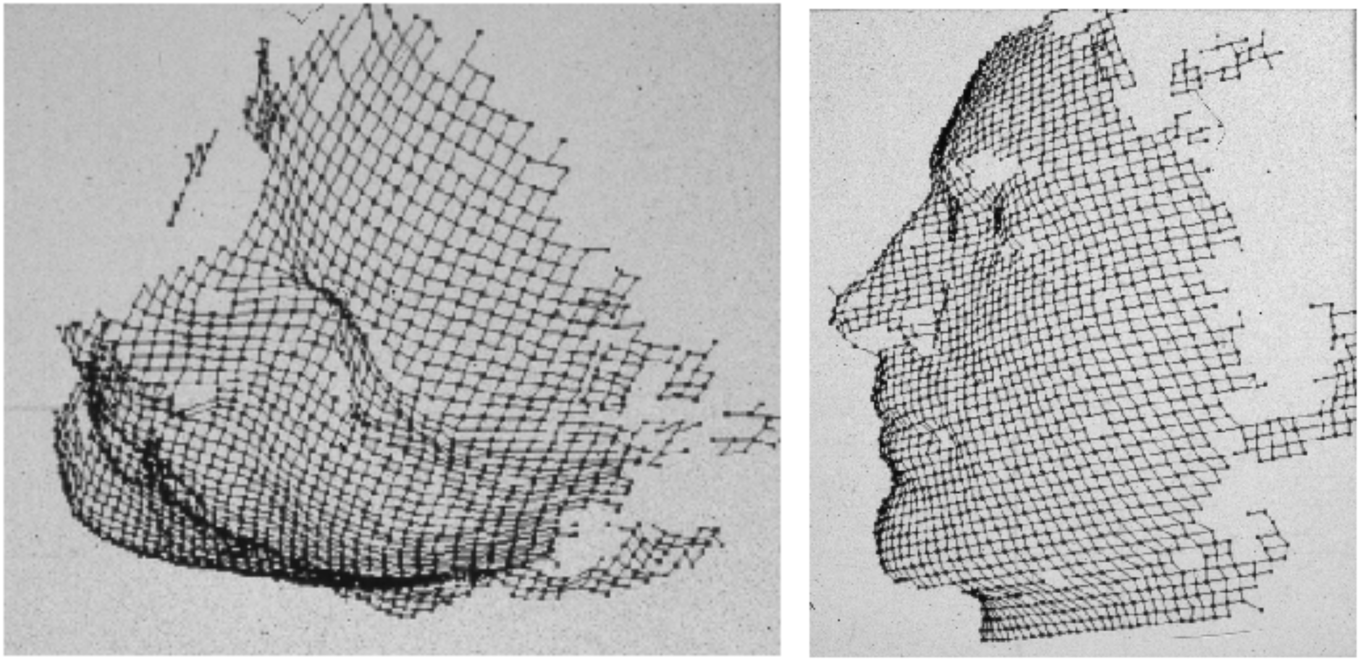


One-shot implementation

KULeuven ‘81: checkerboard pattern with column code

example :

3D reconstruction for the example



An application in agriculture

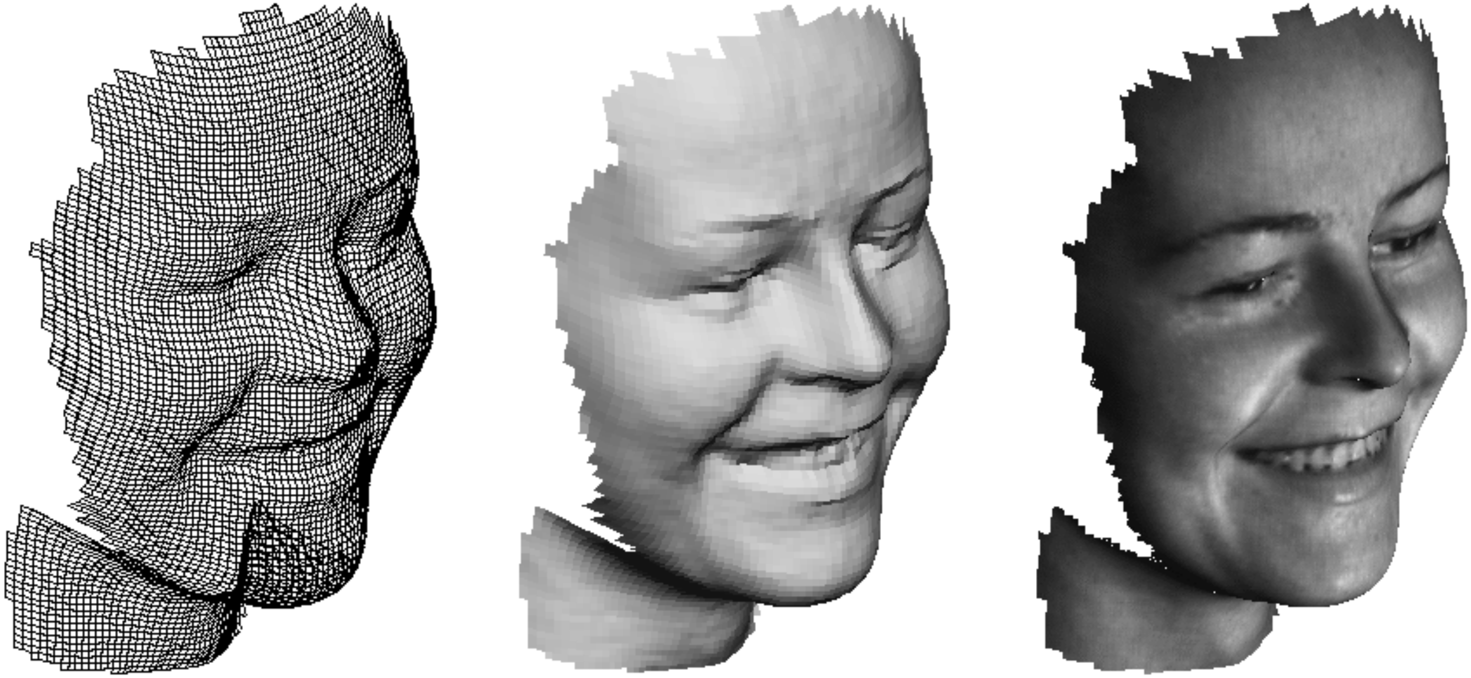
One-shot 3D acquisition

Leuven ShapeCam

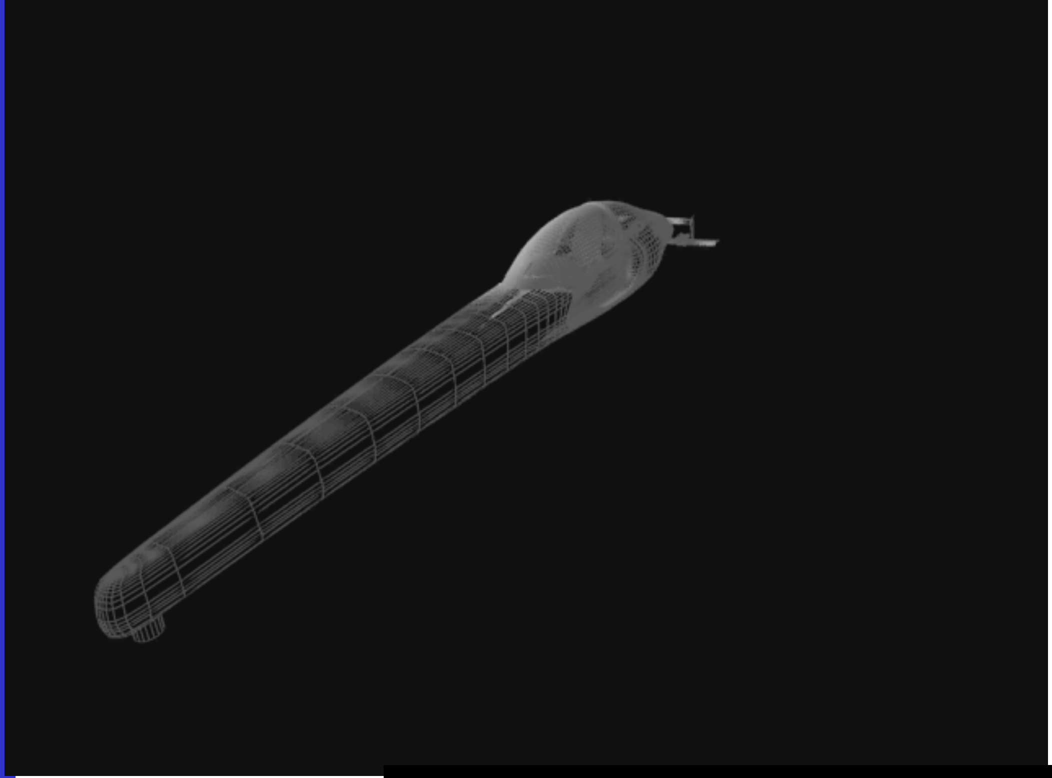
Shape + texture often needed

Higher resolution

Texture is also extracted



Computer Vision

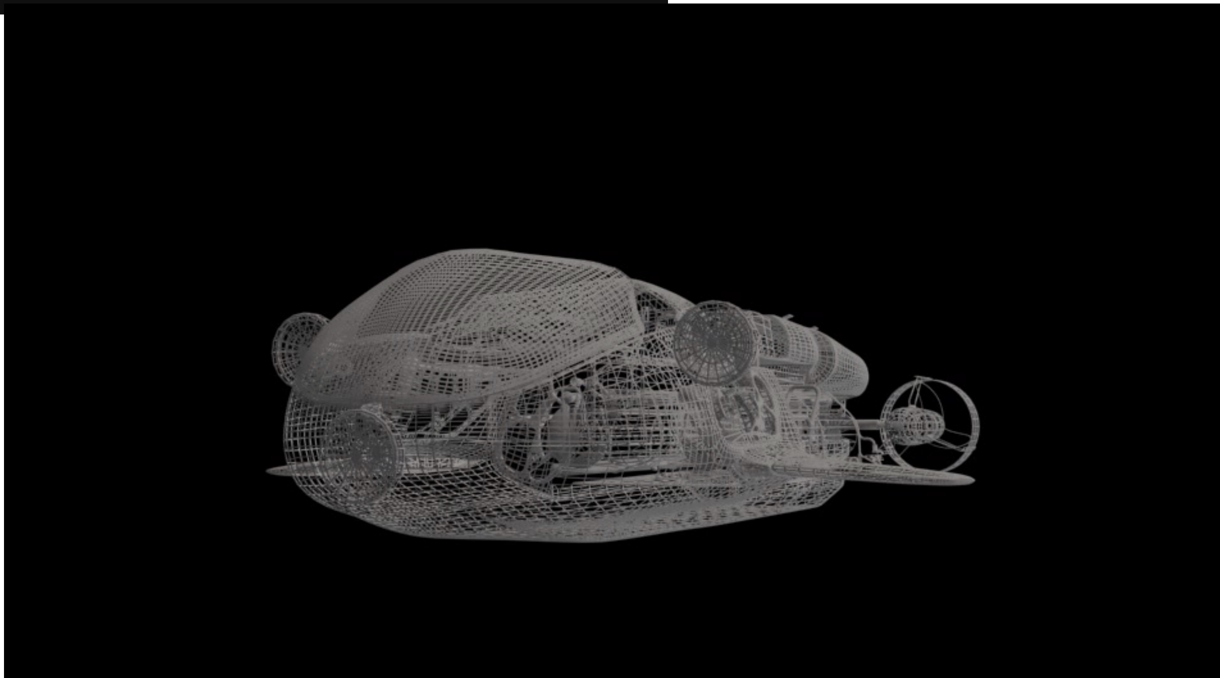


James Bond

Die another day

Lara Croft

Thomb Raider



Active triangulation

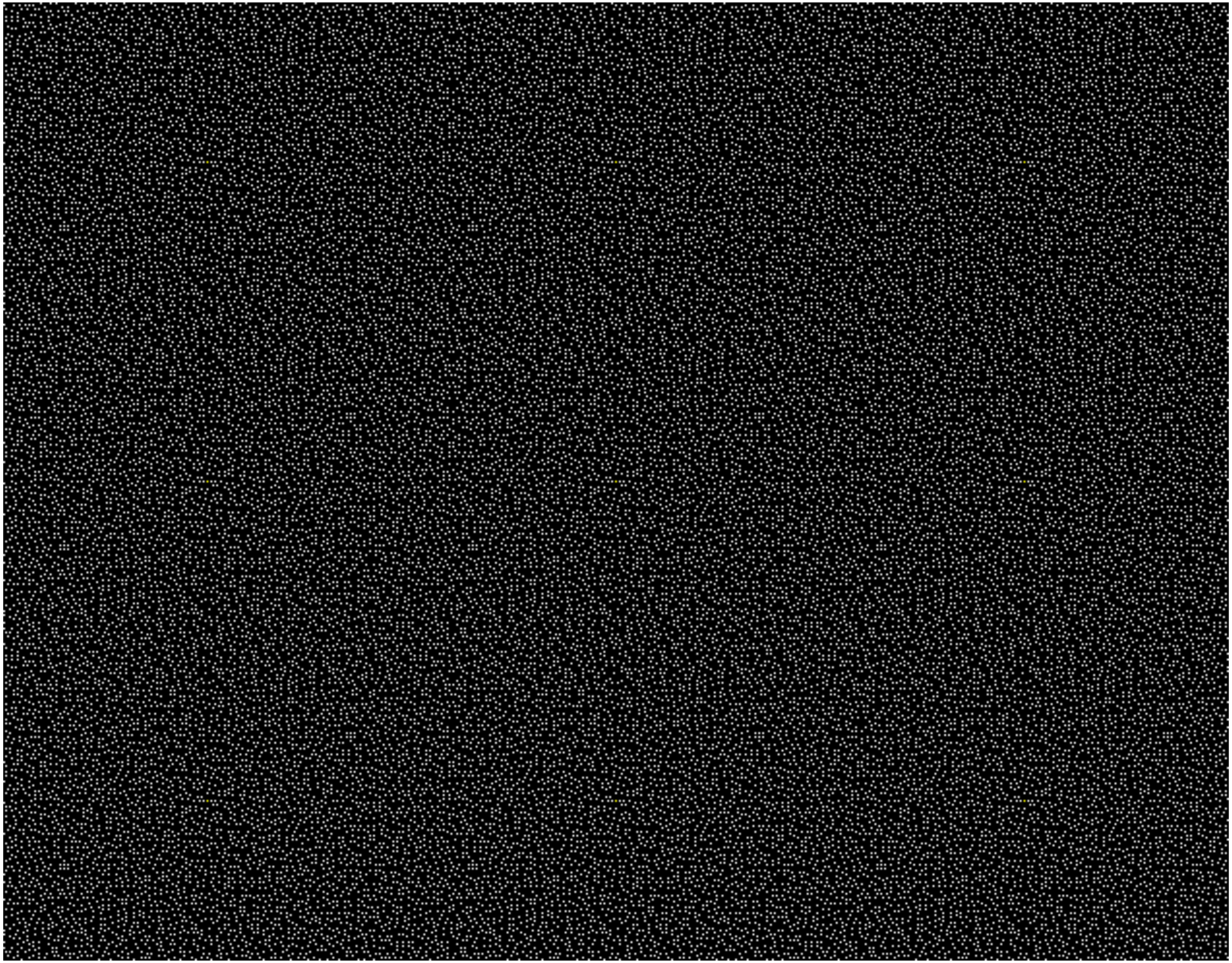
Recent, commercial example

Kinect 3D camera, affordable
and compact solution by Microsoft.

Projects a 2D point pattern in the NIR,
to make it invisible to the human eye

Computer
Vision

Kinect: 9x9 patches with locally unique code

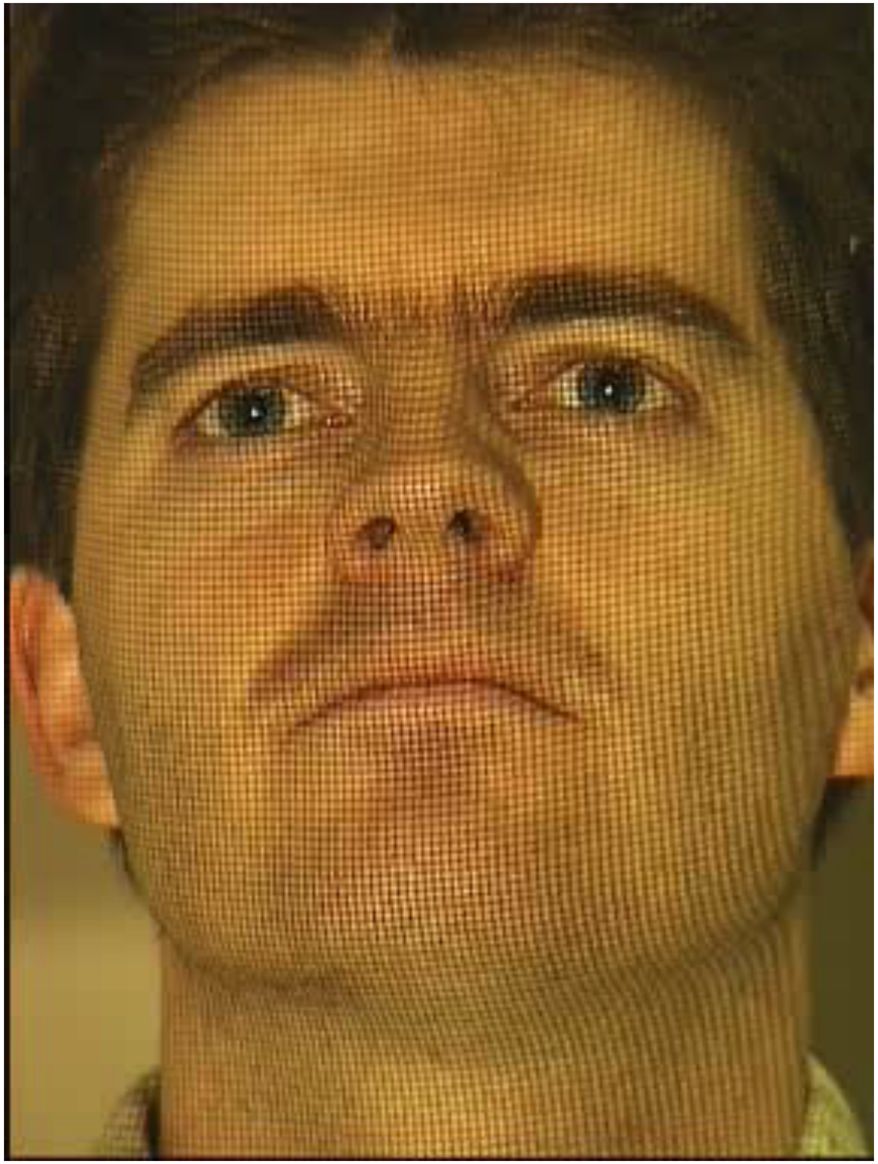


Kinect as one-shot, low-cost scanner

Excerpt from the dense NIR dot pattern:

http://research.microsoft.com/apps/video/default.aspx?i

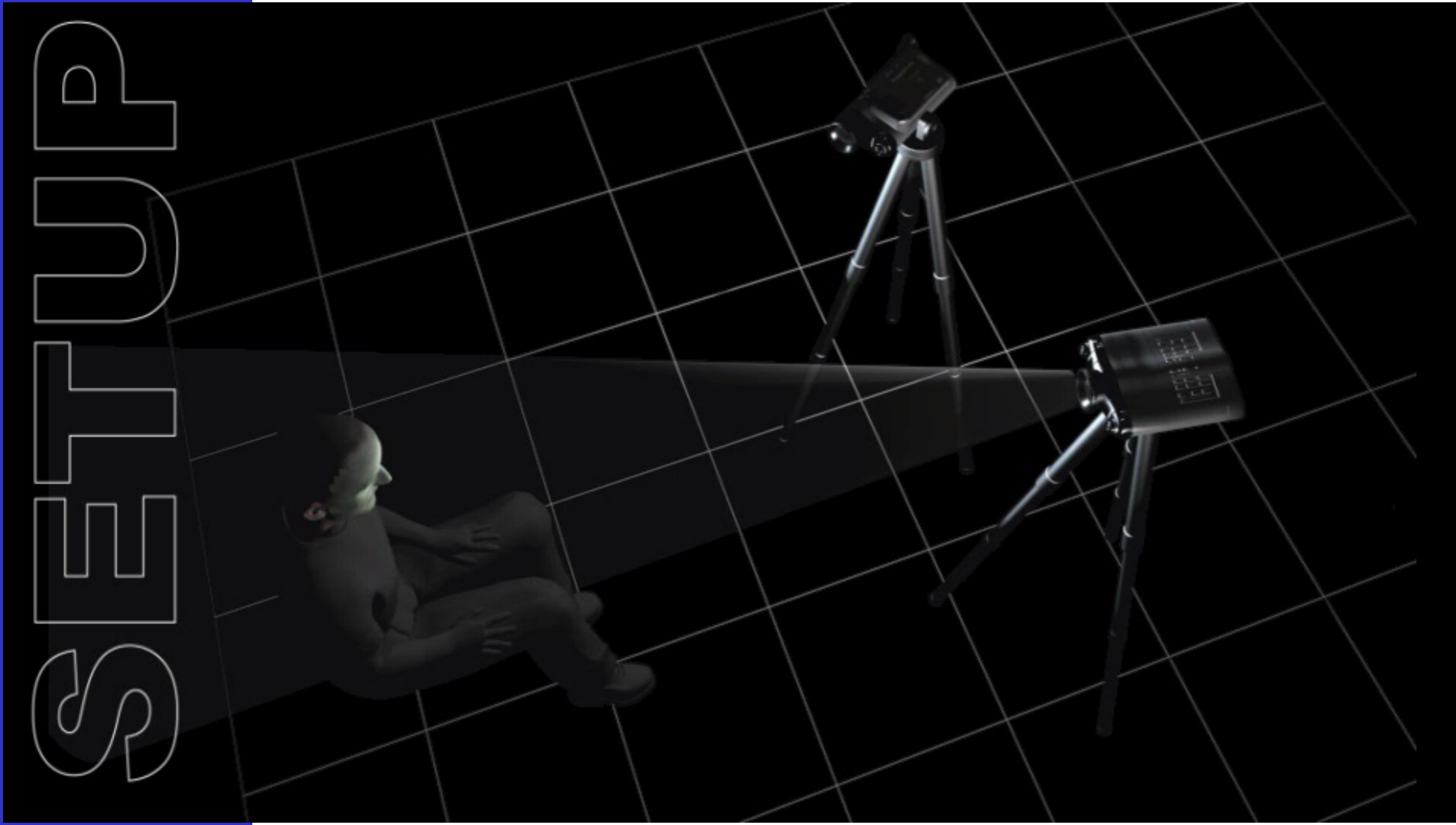
Face animation - input



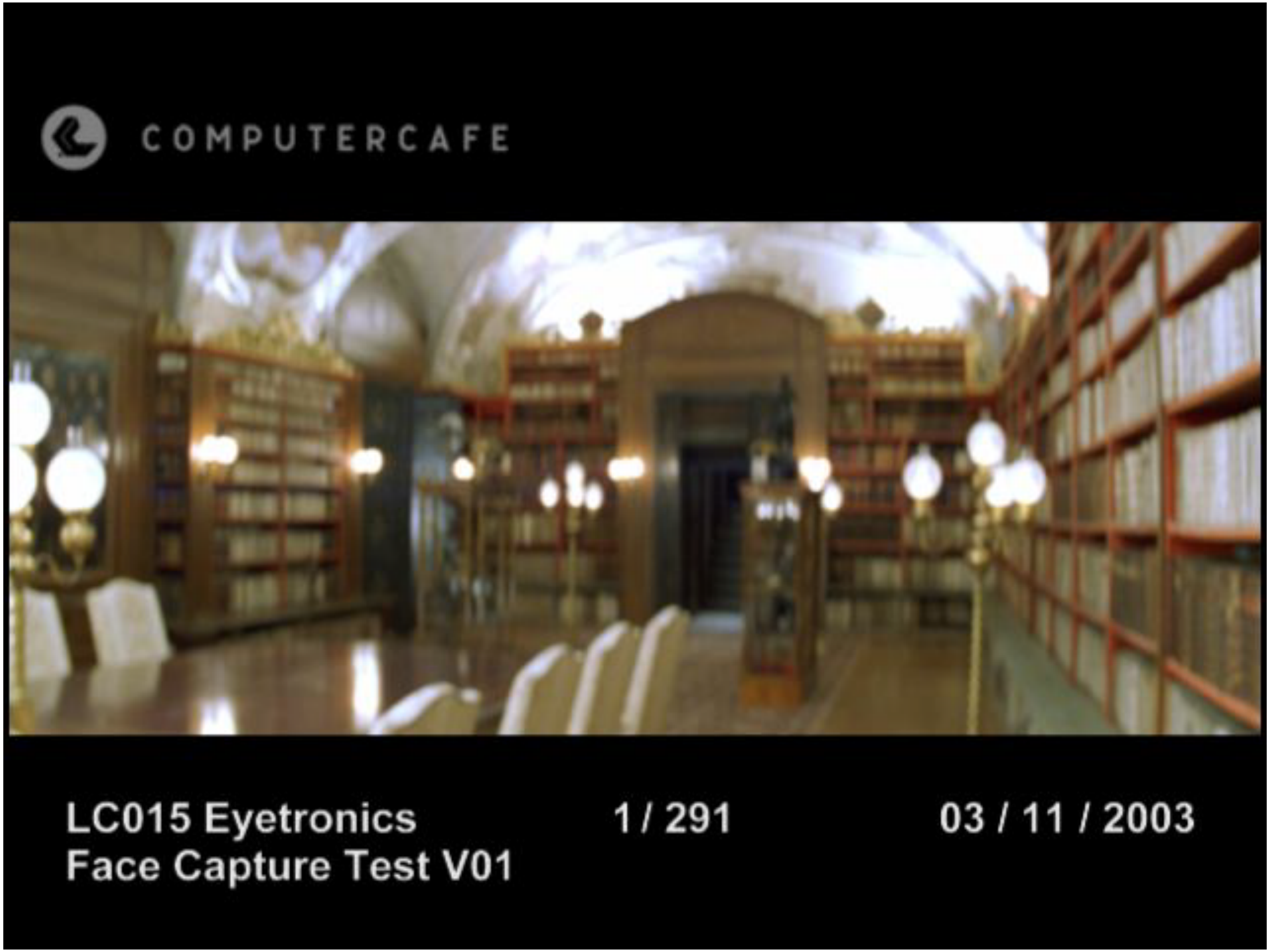
Face animation – replay + effects

Facial motion capture

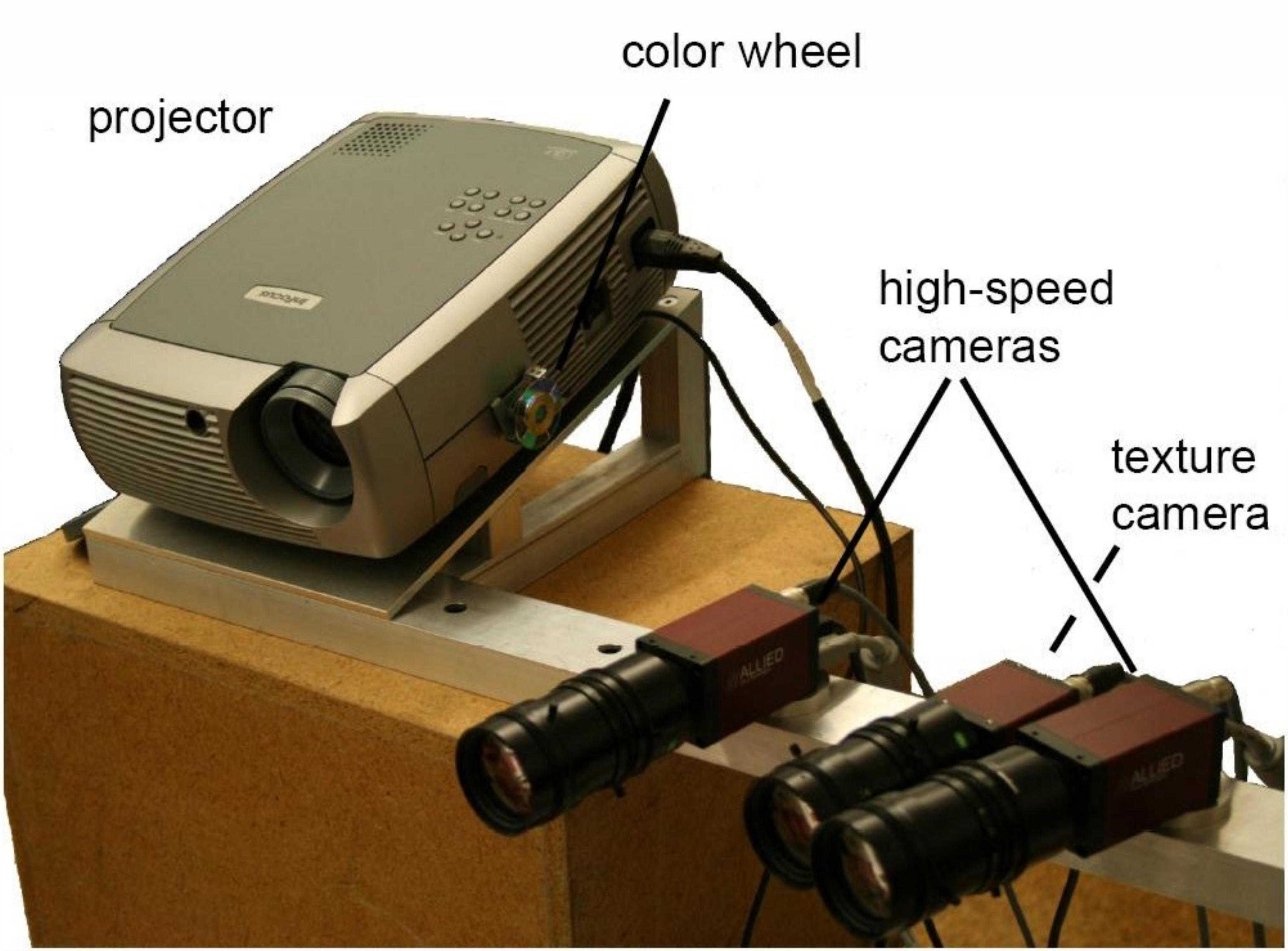
motion capture for *League of Extraordinary Gentlemen*



Facial motion capture



Phase shift



Phase shift

$$I_r = A + R\cos(\phi - \theta)$$

$$I_g = A + R\cos(\phi)$$

$$I_b = A + R\cos(\phi + \theta)$$

1. detect phase from 3 subsequently projected cosine patterns, shifted over 120 degrees
2. unwrap the phases / additional stereo
3. texture is obtained by summing the 3 images / color camera w. slower integration

Phase shift

$$A = \frac{I_r + I_g + I_b}{3}$$

$$\phi = \arctan\left(\tan\left(\frac{\theta}{2}\right) \frac{I_r - I_b}{2I_g - I_r - I_b} \right)$$

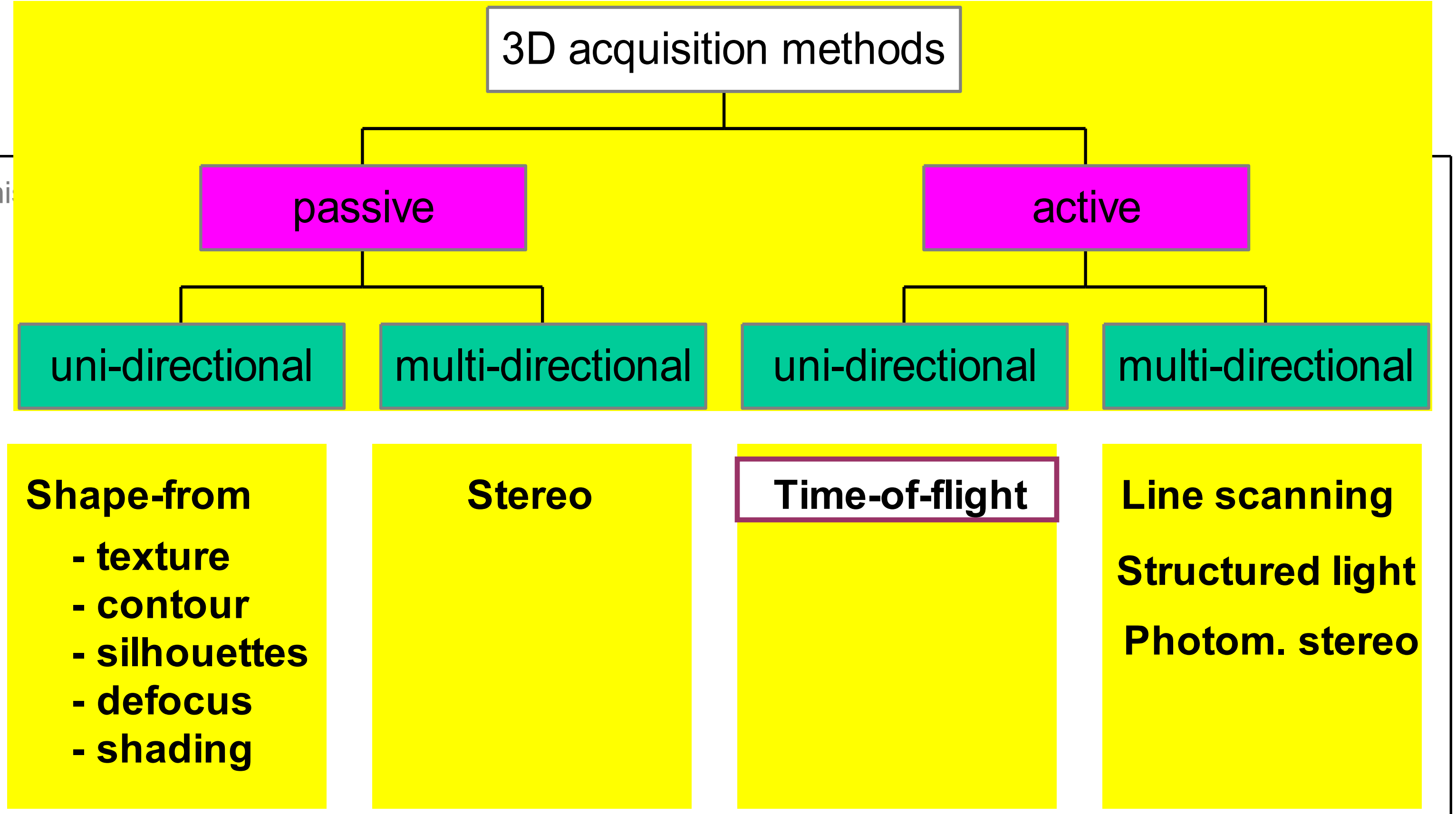
4D acquisition

Motion retargetting, from 3D phase shift scans

Face/Off: Live Facial Puppetry

PaperID 102

3D acquisition taxonomy



3D acquisition methods

- passive
  - uni-directional
  - multi-directional
- active
  - uni-directional
  - multi-directional

Shape-from

- **texture**
- **contour**
- **silhouettes**
- **defocus**
- **shading**

Stereo

Time-of-flight

Line scanning

Structured light

Photom. stereo

Time-of-flight

measurement of the time a modulated light signal needs to travel before returning to the sensor

this time is proportional to the distance

waves :

1. *radar*	low freq. electromagnetic
2. *sonar*	acoustic waves
3. *optical radar*	optical waves

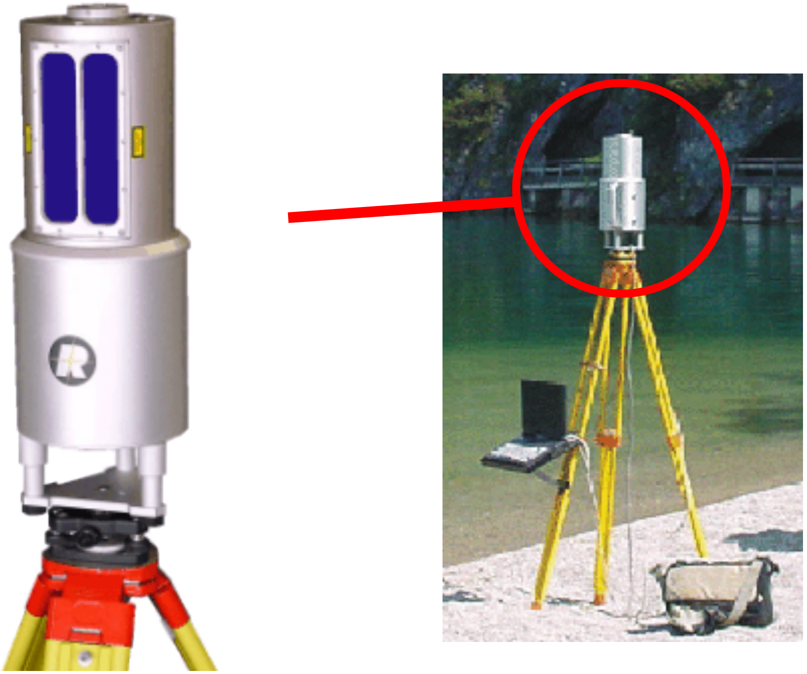
working principles :

1. pulsed
2. phase shifts

Time-of-flight

Example 1: Cyrax

Example 2: Riegl



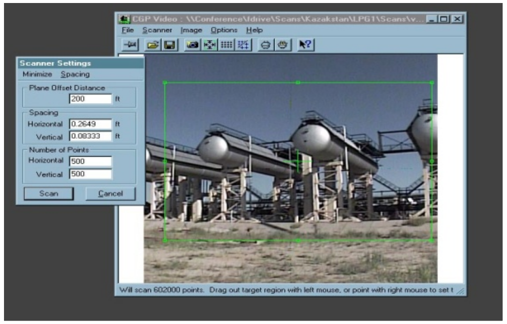
Time-of-flight: example

Cyrax ™

3D Laser Mapping System

Cyrax

Accurate, detailed, fast measuring



Scanner Settings

Plane Offset Distance: 200 ft

Spacing

Horizontal: 0.2649 ft

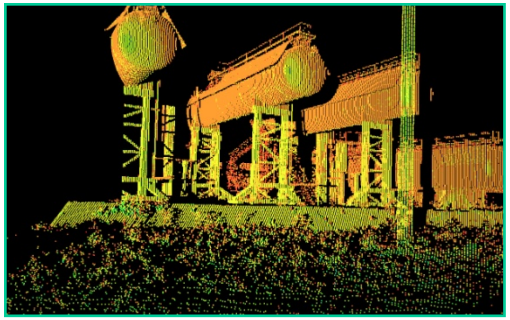
Vertical: 0.08333 ft

Number of Points

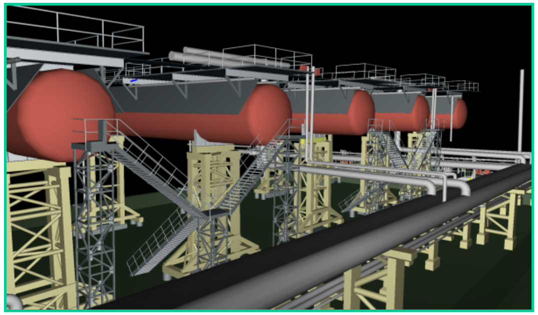
Horizontal: 500

Vertical: 500

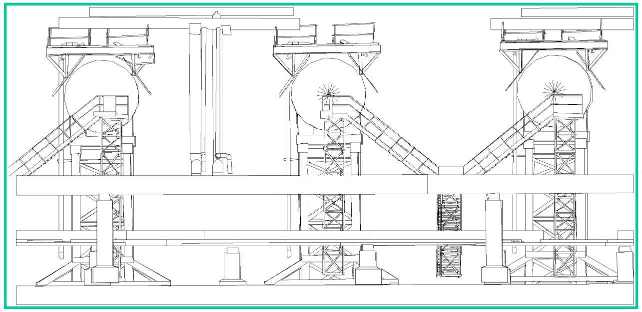
Will scan 602000 points. Drag out target region with left mouse, or point with right mouse to set t



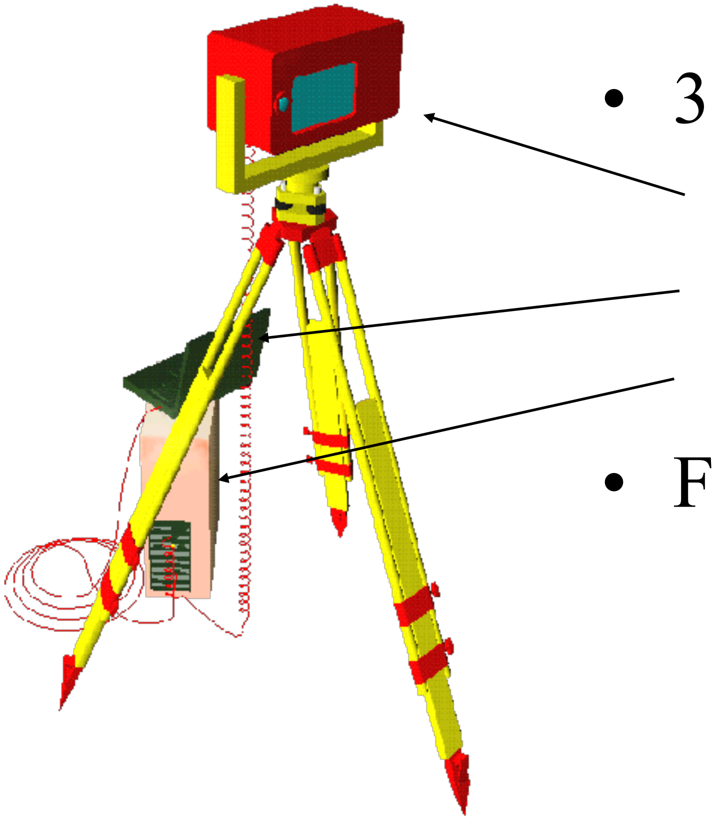
2D / 3D CAD



Integrated modeling



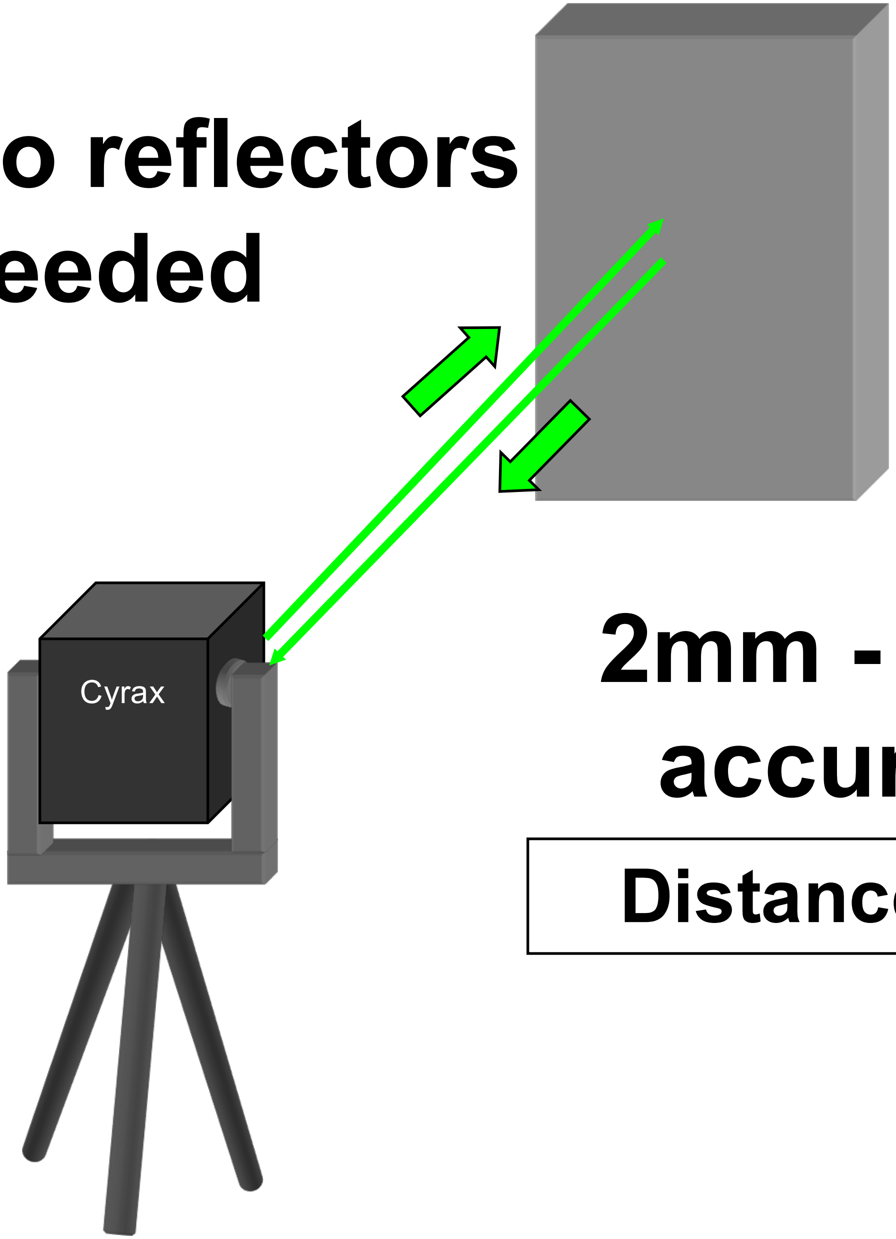
Cyrax



- 3 Components
  - Laser Scanner
  - Laptop Computer & Software
  - Electronics & Power Supply
- Field Portable

Pulsed laser (time-of-flight)

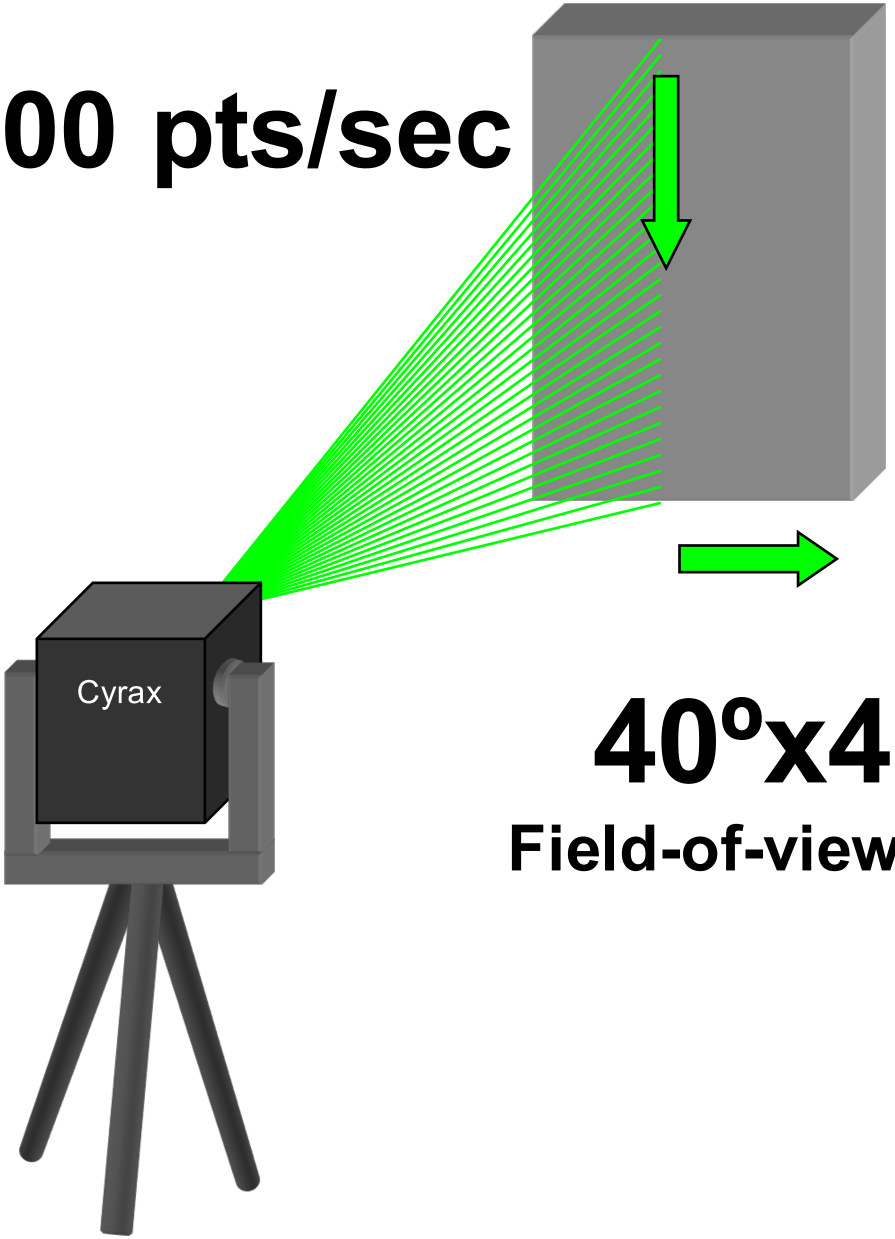
No reflectors needed



2mm - 6mm accuracy

$$\text{Distance} = C \times \Delta T \div 2$$

Laser sweeps over surface



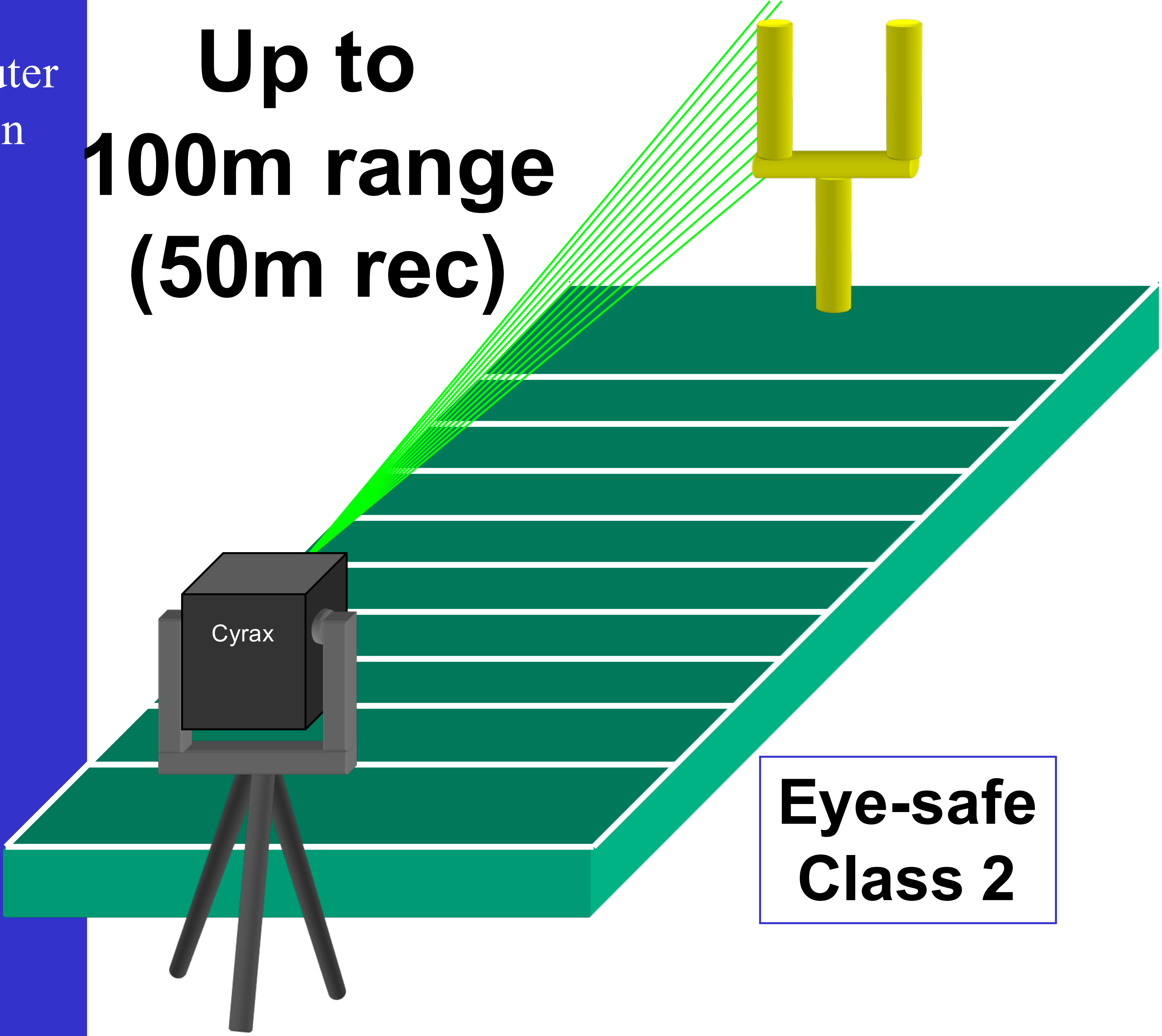
800 pts/sec

2mm min pt-to-pt spacing

40°x40°

Field-of-view (max)

Up to 100m range (50m rec)

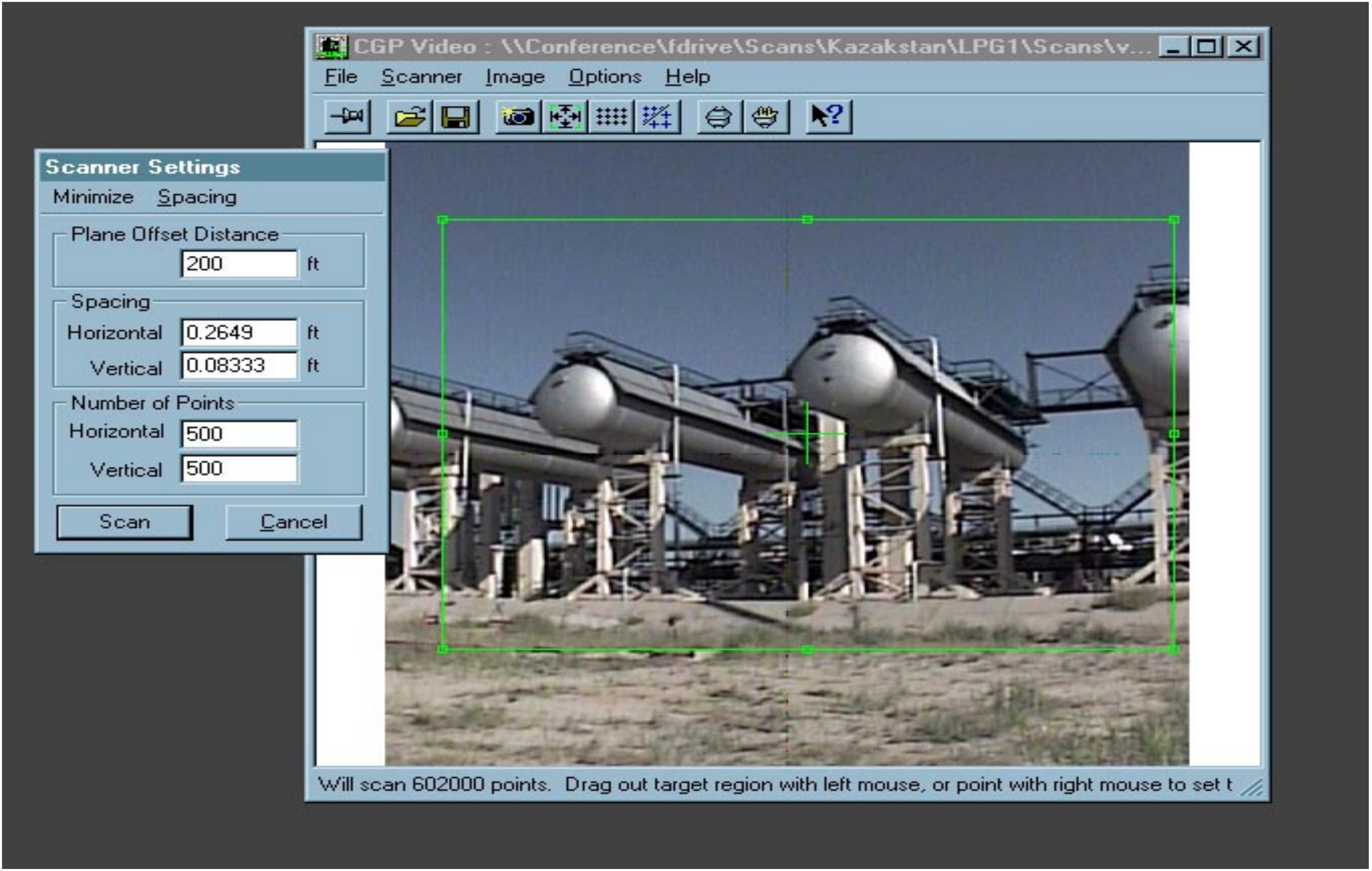


Eye-safe Class 2

Cyrax is *also* a visualization tool

Cyrax detects the intensity of each reflected laser pulse and colors it

Step 1:
Target the structure



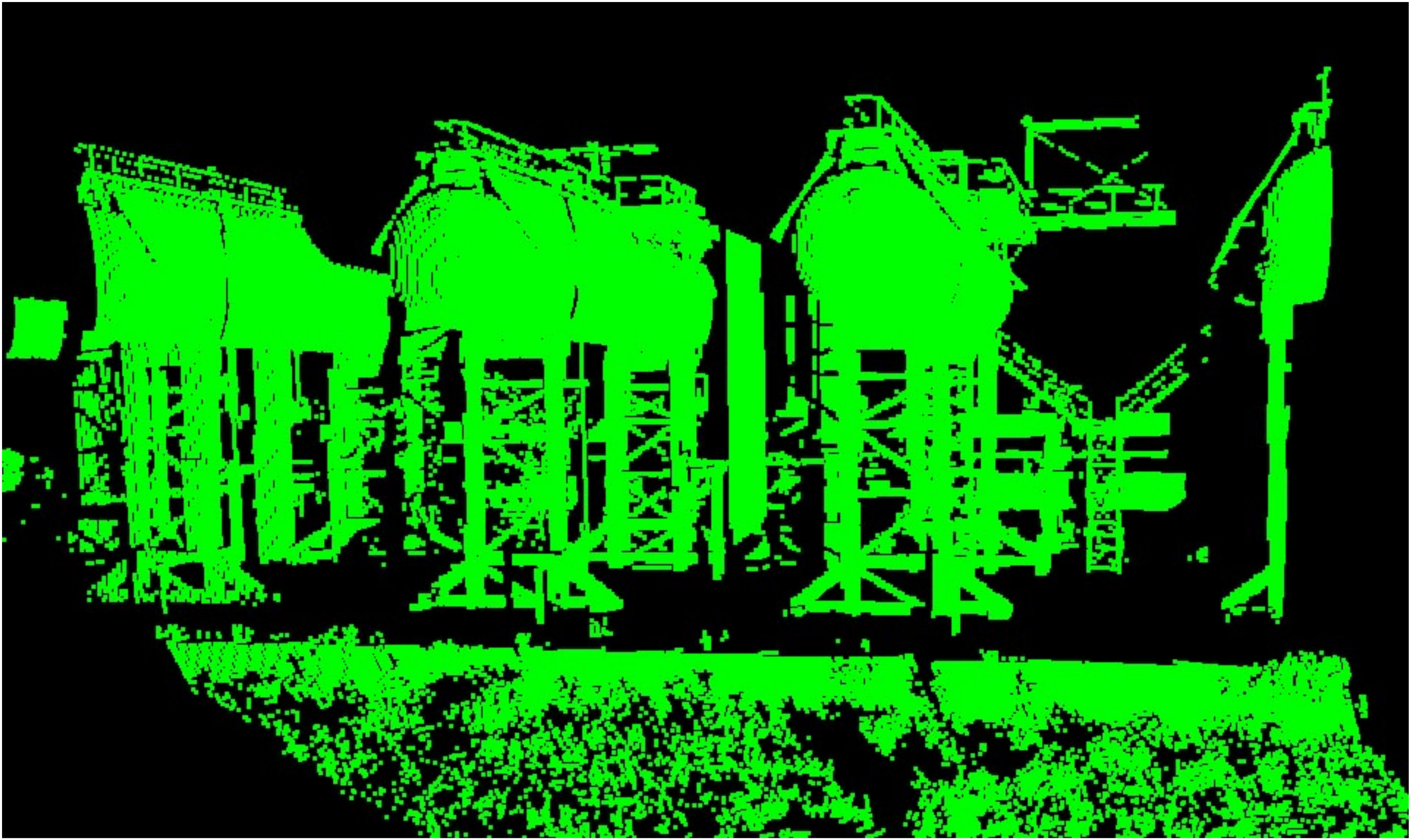
Plane Offset Distance: 200 ft

Spacing
Horizontal: 0.2649 ft
Vertical: 0.08333 ft

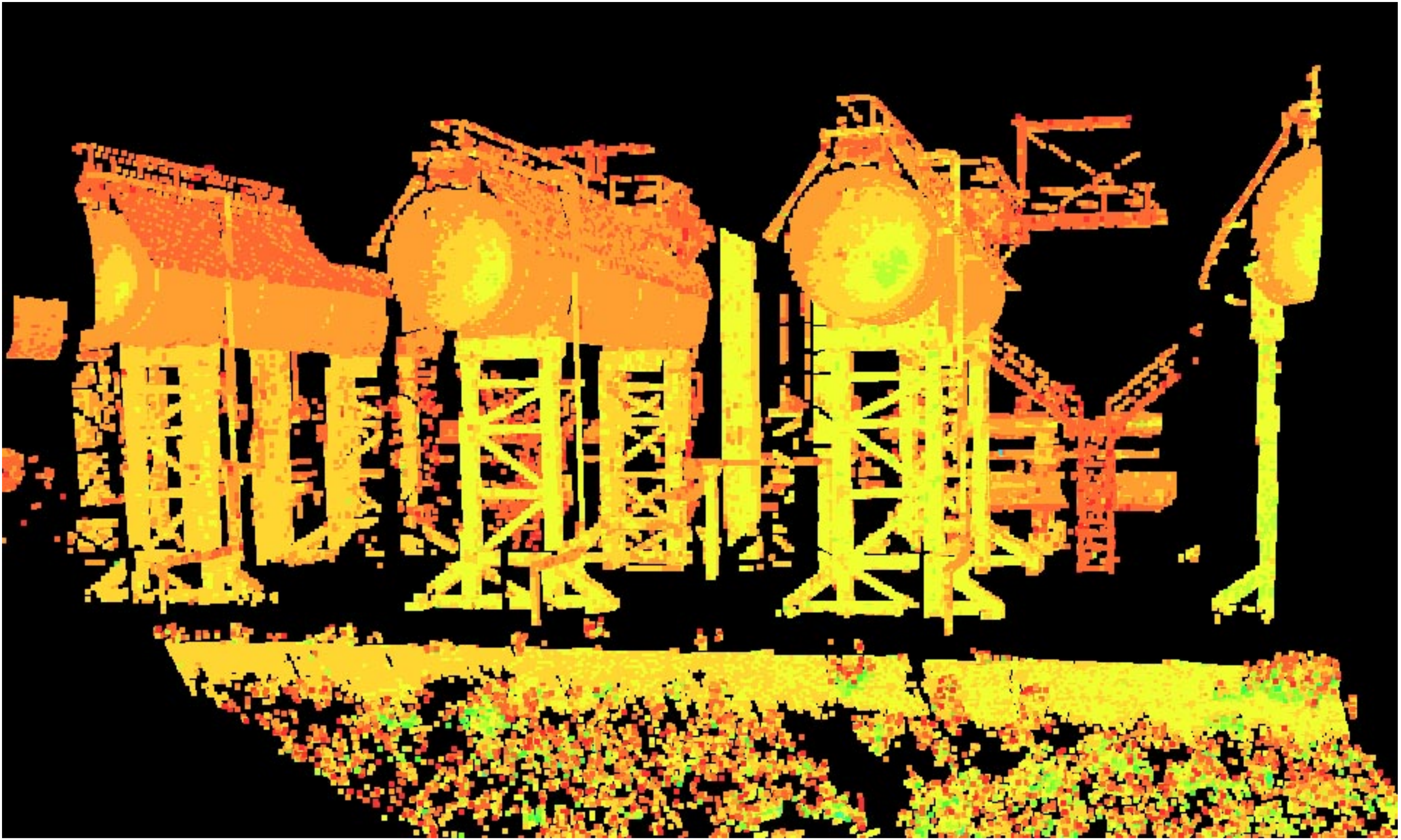
Number of Points
Horizontal: 500
Vertical: 500

Will scan 602000 points. Drag out target region with left mouse, or point with right mouse to set t

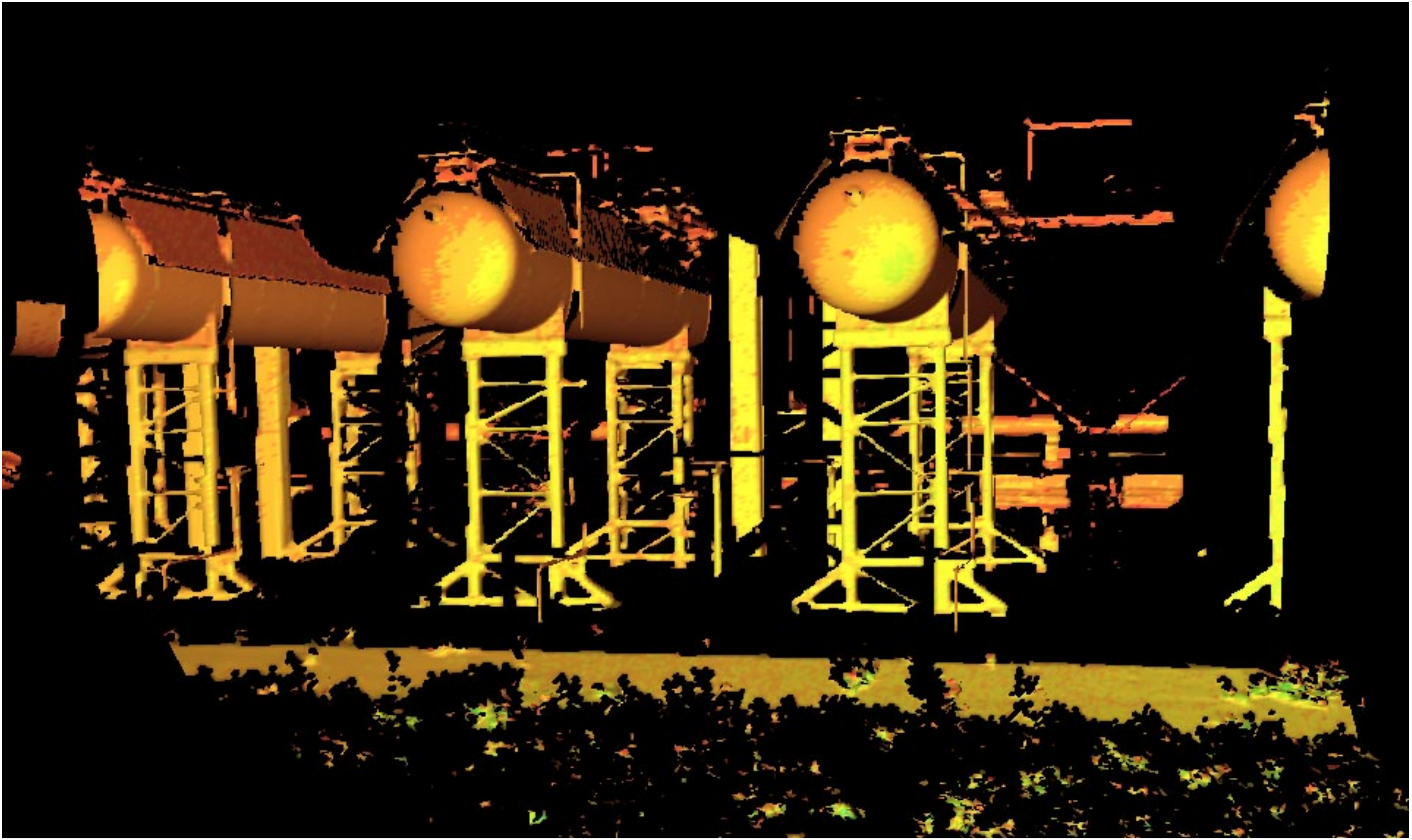
Step 2:
Scan the structure



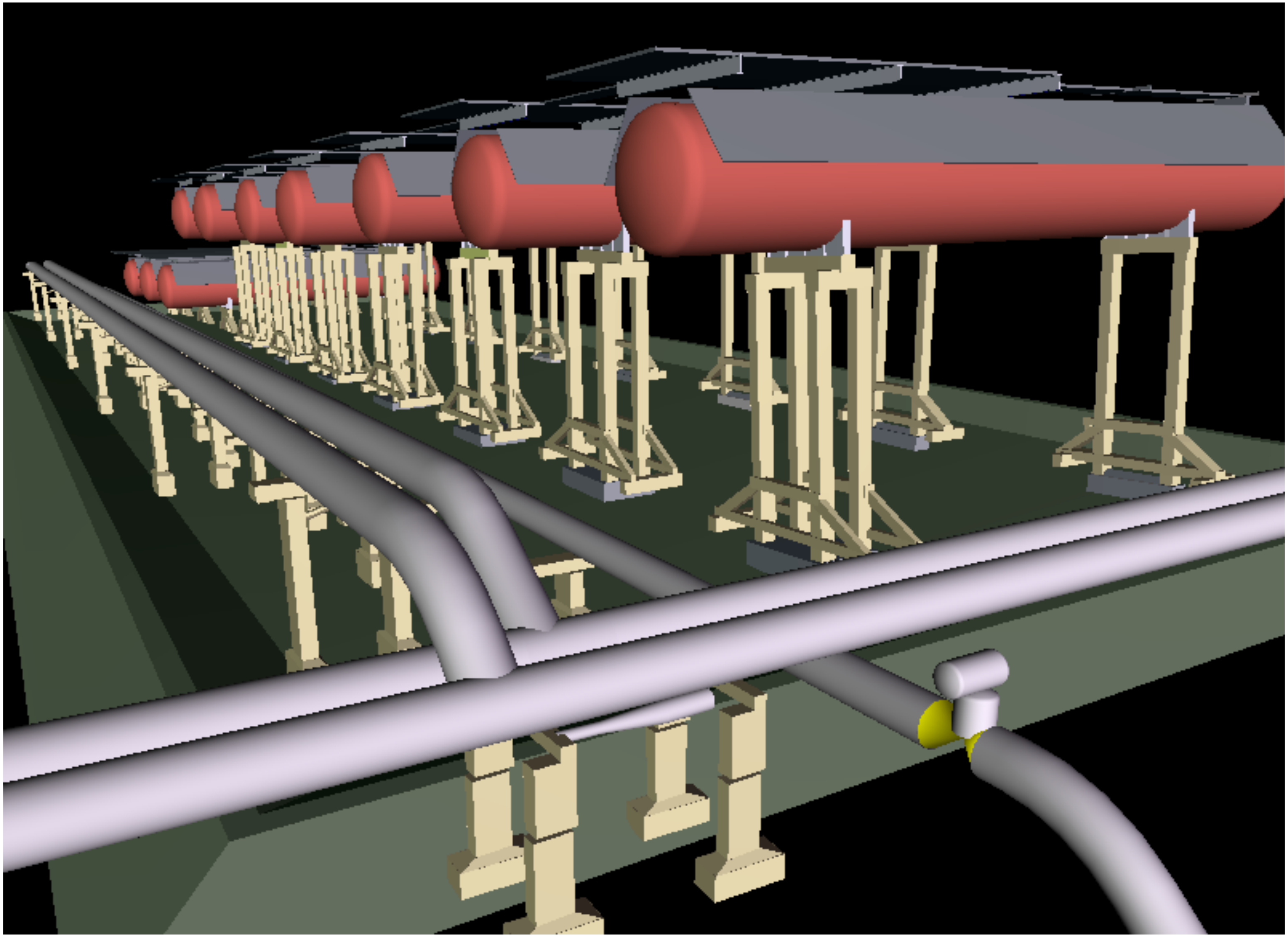
Step 3:
Color the points

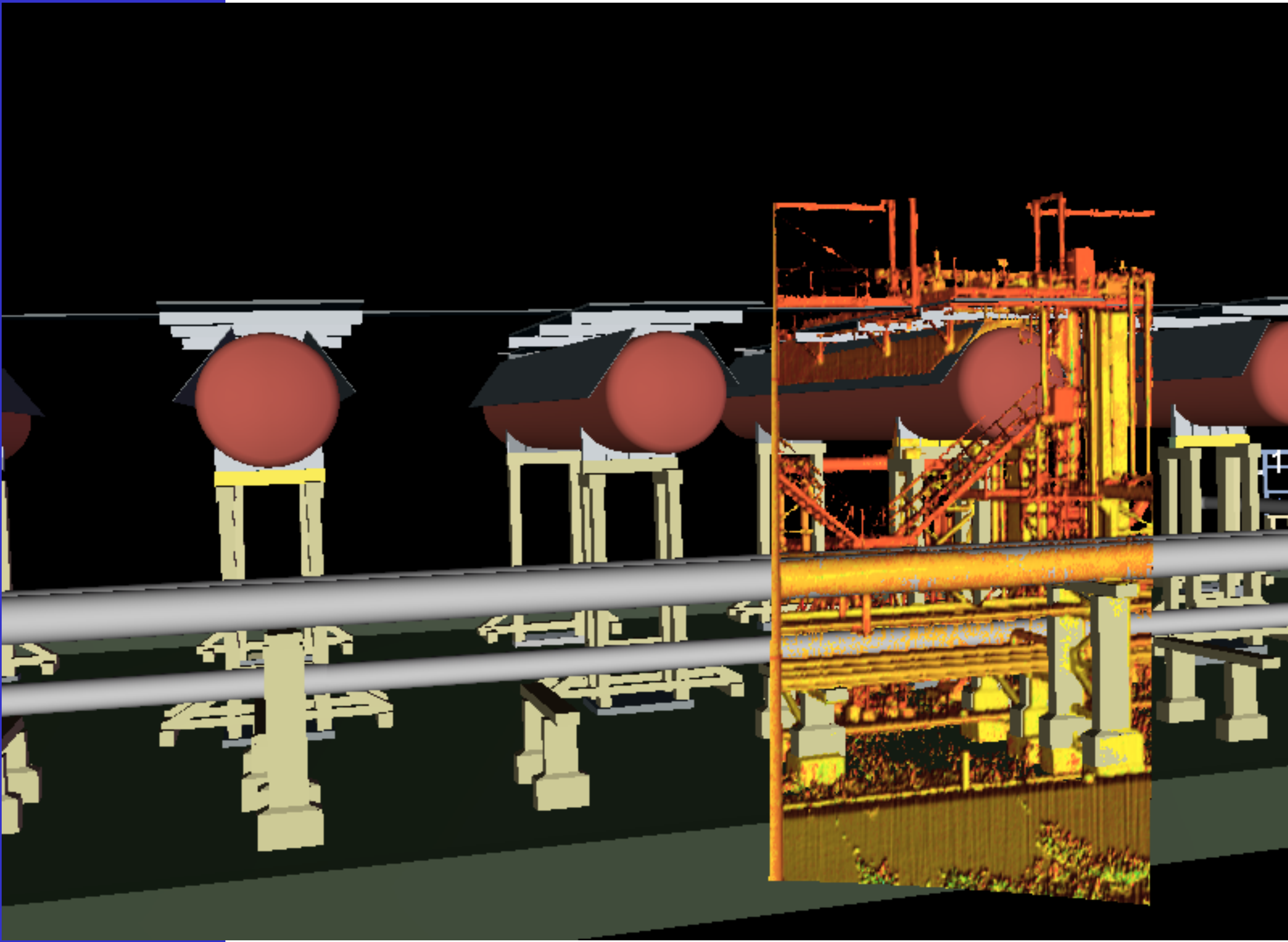


Step 4:
Model fitting in-the-field



Result

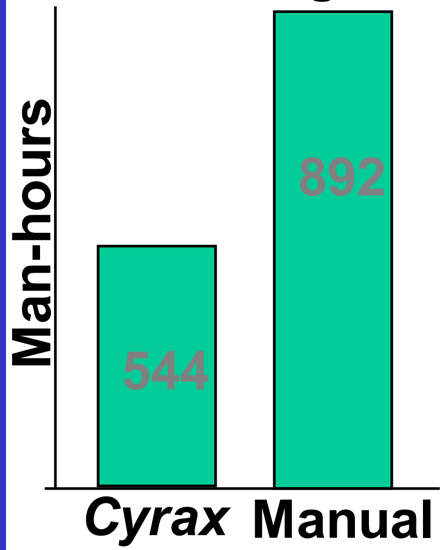




Project: As-built of Chevron hydrocarbon plant

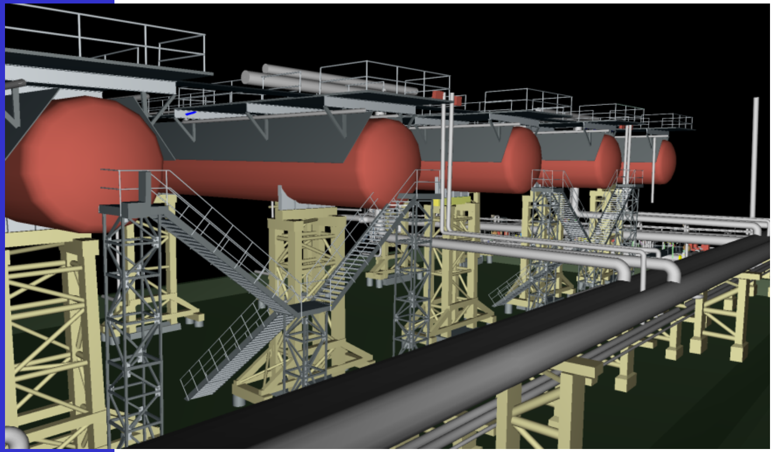
- 400’x500’ area
- 10 vessels; 5 pumps
- 6,000 objects
- 81 scans from 30 tripod locations
- *Cyrax* field time = 50 hrs

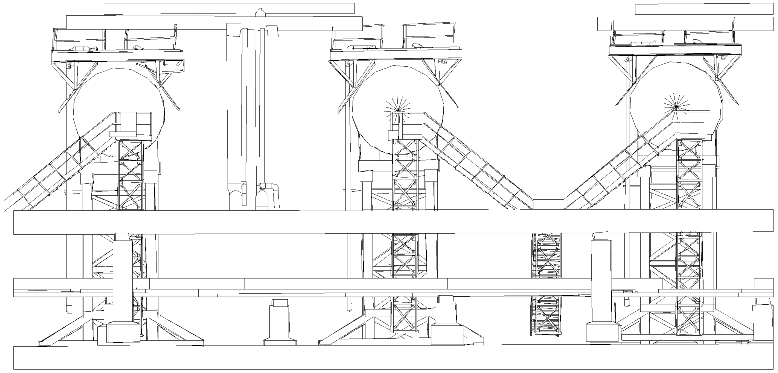
Cost Benefits


Measuring & modeling

Added Value Benefits

- Greater detail & no errors
- Higher accuracy
- Fewer construction errors
- 6 week schedule savings

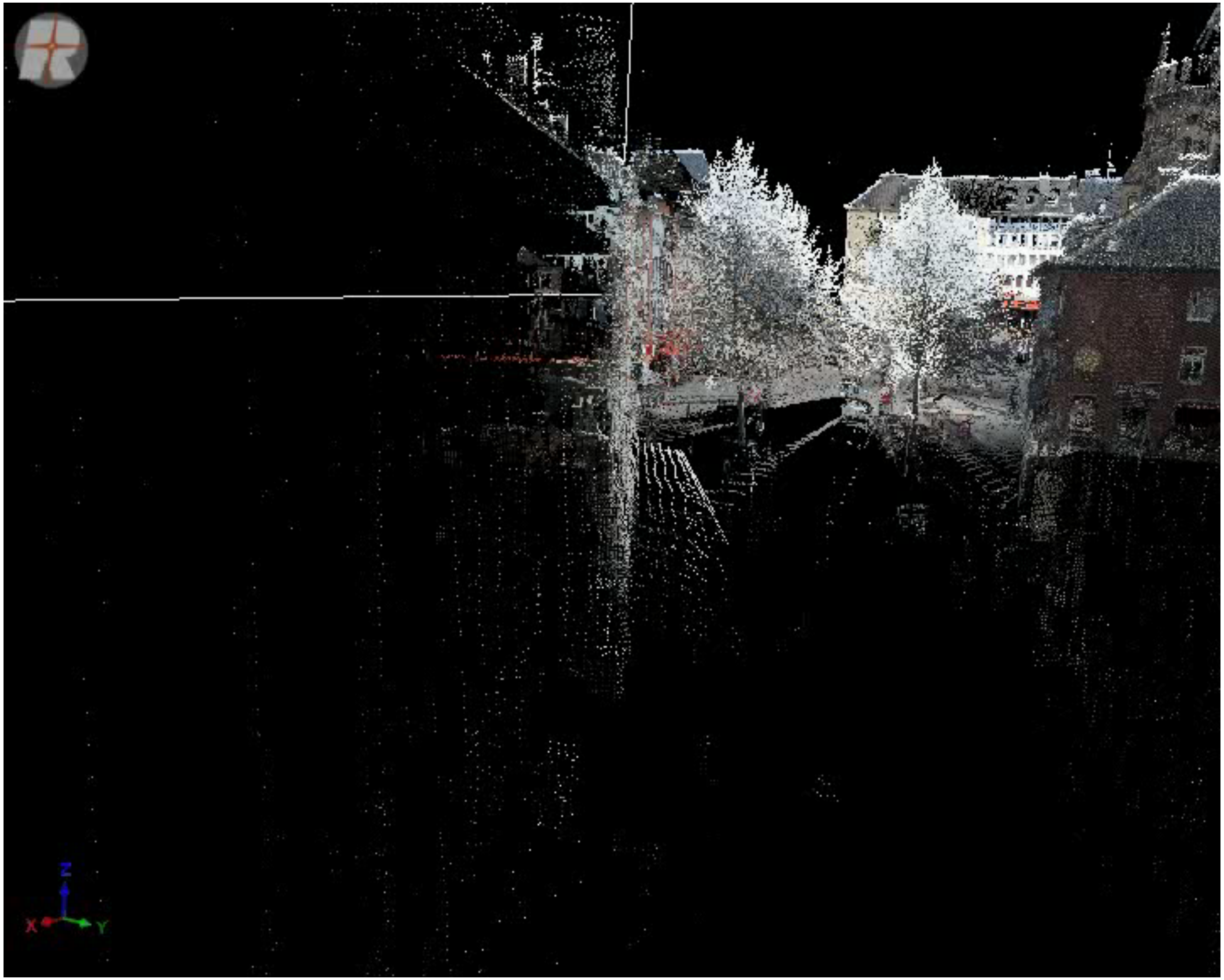




Application
Modeling movie sets

Image courtesy of Tippett Studio

Lidar data with Riegl LMS-Z390i

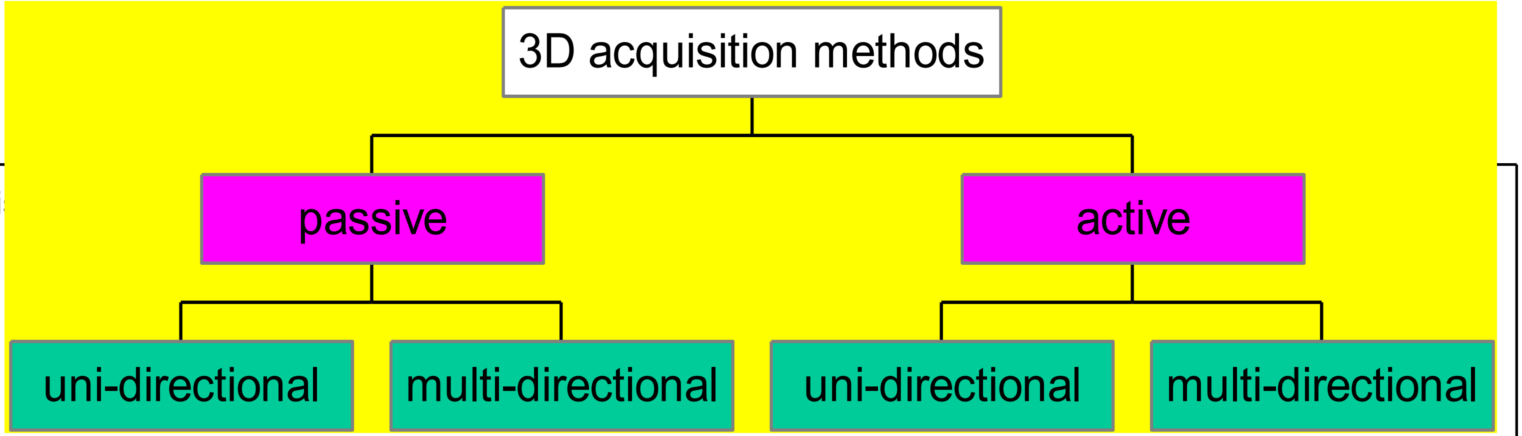


courtesy of RWTH Aachen, L. Kobbelt et al.

Comparison Lidar - passive

Image courtesy of Tippett Studio

3D acquisition taxonomy



3D acquisition methods

passive

active

uni-directional

multi-directional

uni-directional

multi-directional

Shape-from

- **texture**
- **contour**
- **silhouettes**
- **defocus**
- **shading**

Stereo

Time-of-flight

Line scanning

Structured light

Photom. stereo

Shape-from-texture

assumes a slanted and tilted surface to have a homogeneous texture

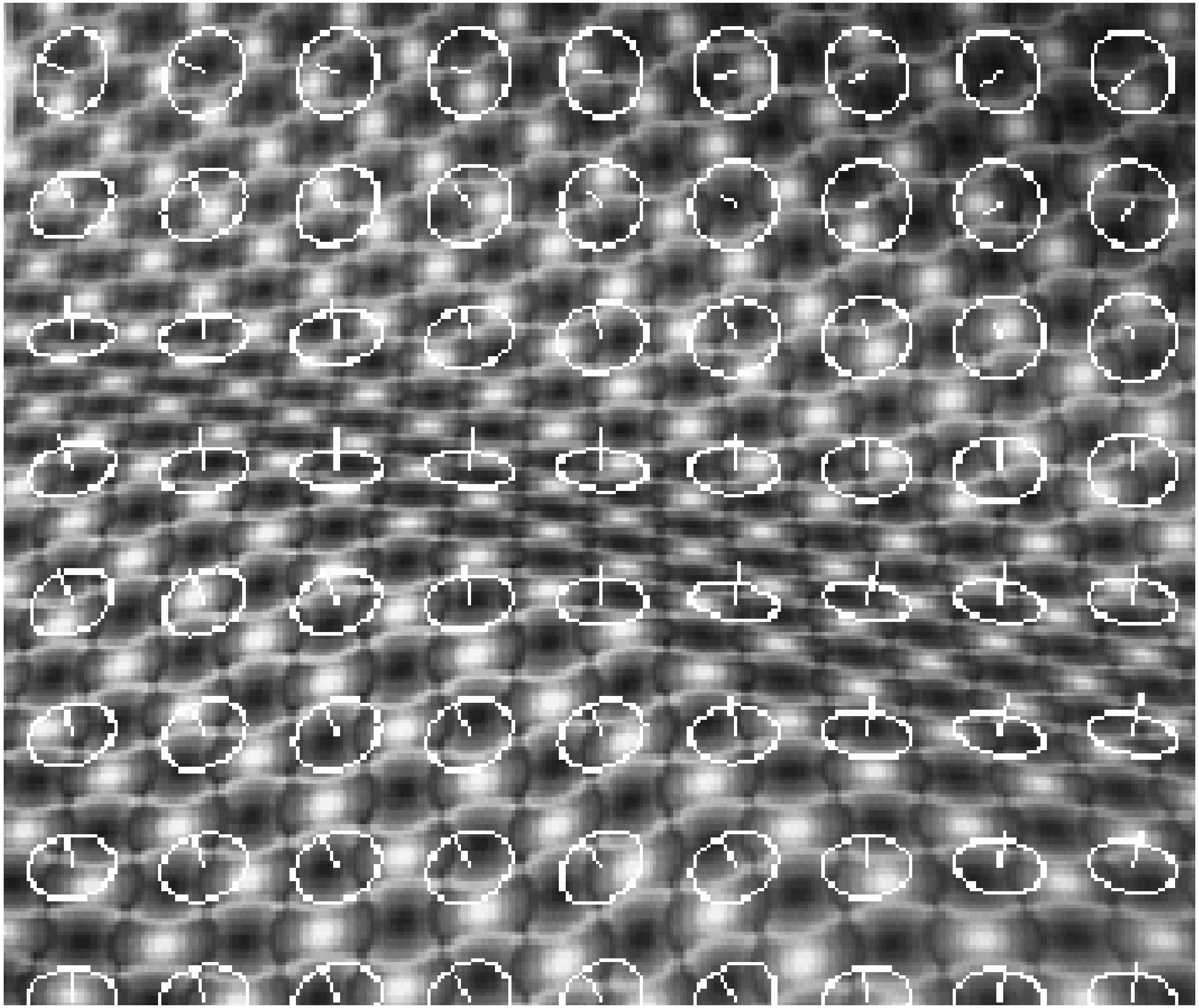
inhomogeneity is regarded as the result of projection

e.g. anisotropy in the statistics of edge orientations

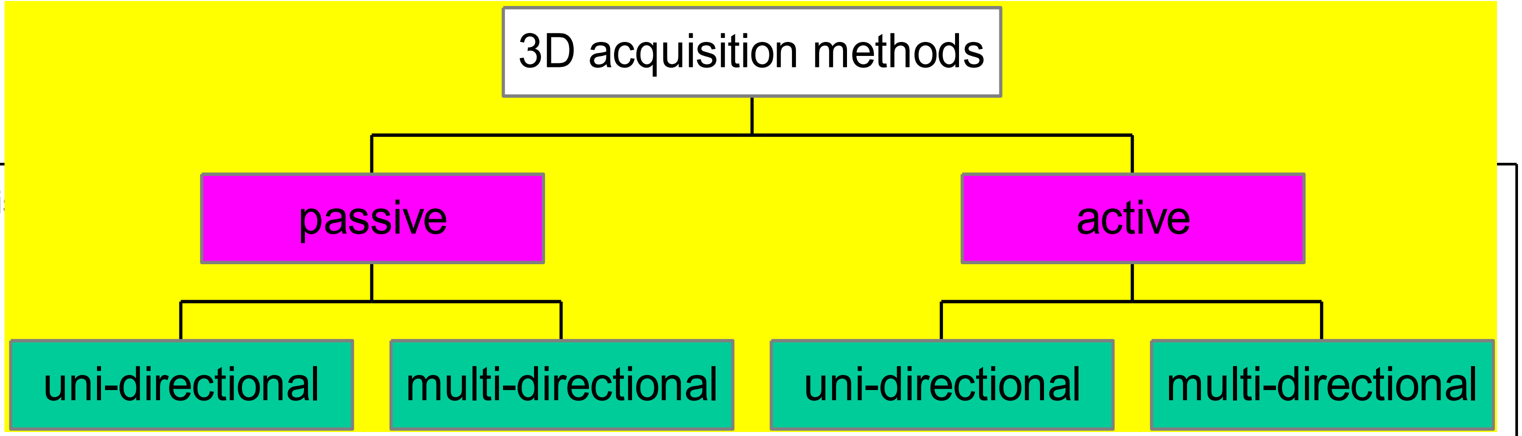
⇓

orientations deprojecting to maximally isotropic texture

Computer Vision



3D acquisition taxonomy



Shape-from
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Structured light

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Shape-from-contour

makes assumptions about contour shape

E.g. the maximization of area over perimeter squared (compactness)

⇓

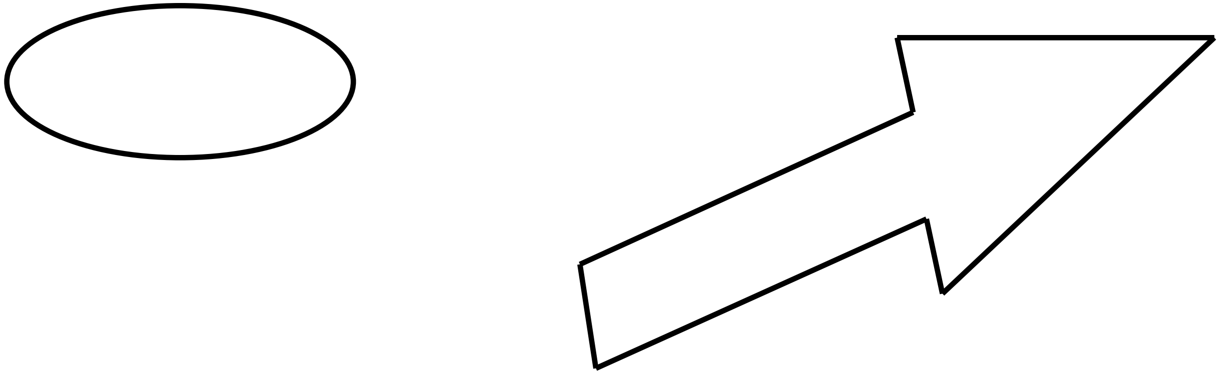
ellipse → circle

E.g. assumption of symmetry

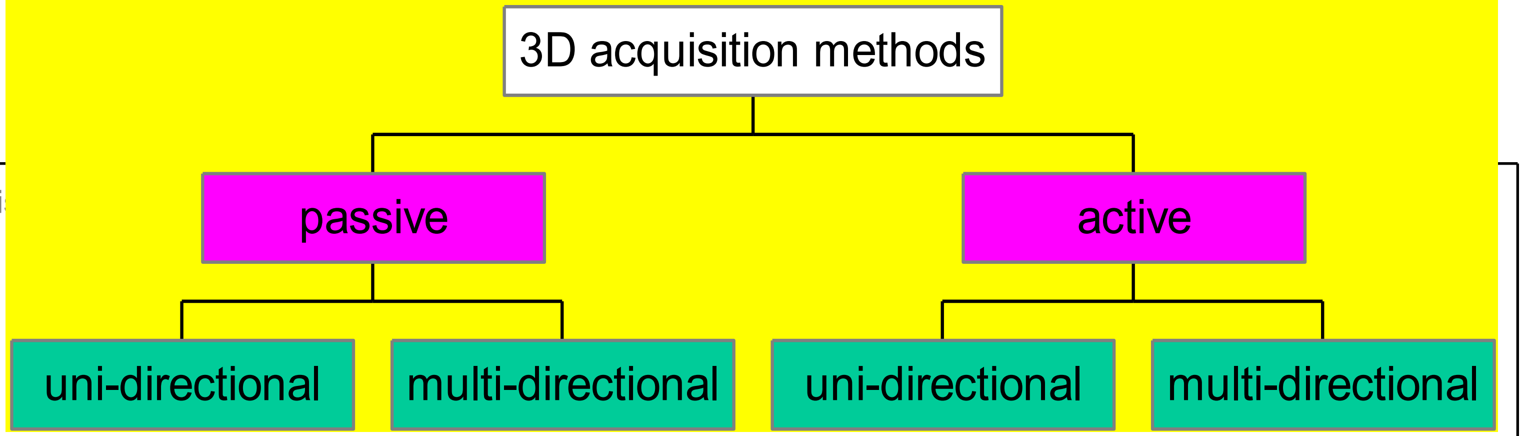
⇓

Symmetric contours → surface of revolution

Shape-from-contour



3D acquisition taxonomy



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passive

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uni-directional

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uni-directional

multi-directional

Shape-from
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Stereo

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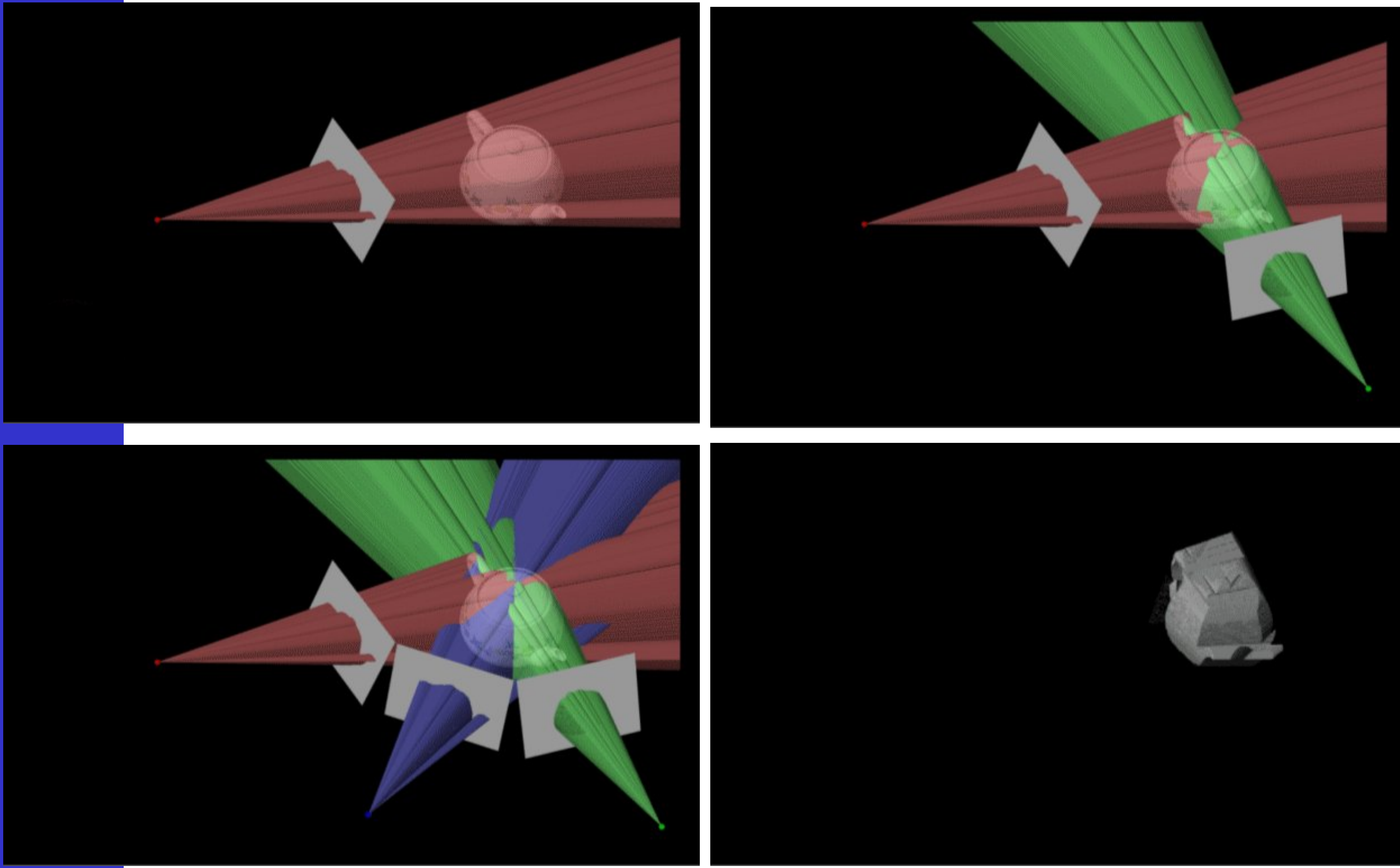
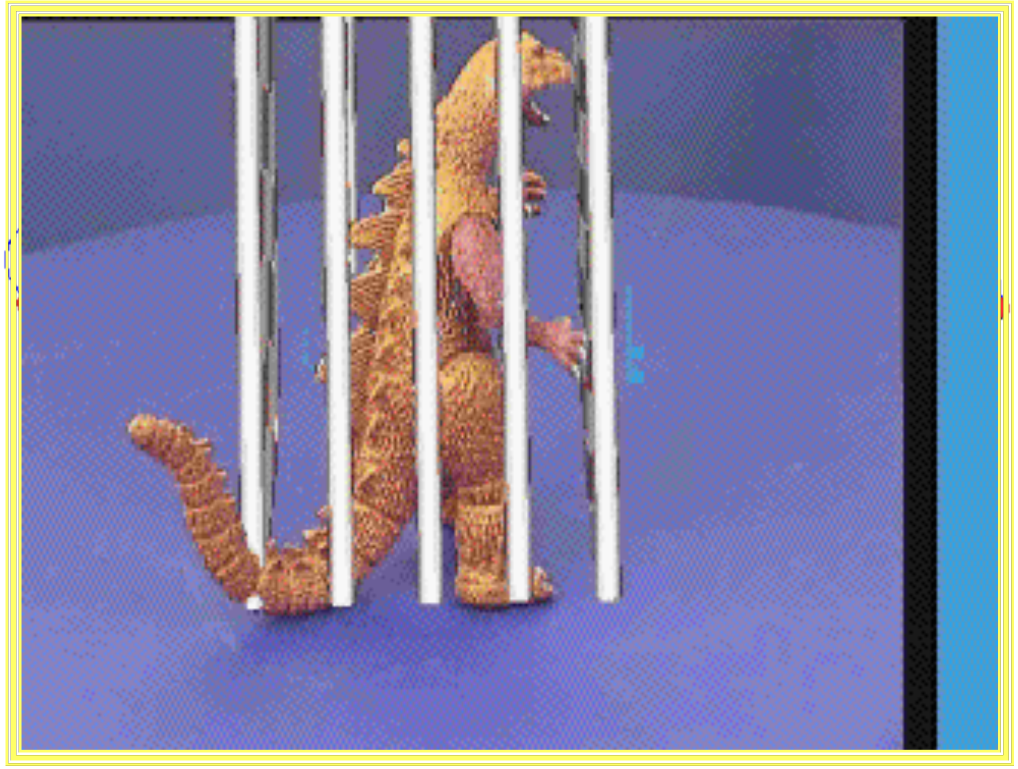
Shape-from-silhouettes



Shape from silhouettes - uncalibrated

tracking of turntable rotation
- **volumetric modeling from silhouettes**
- **triangular textured surface mesh**

Turntable sequence

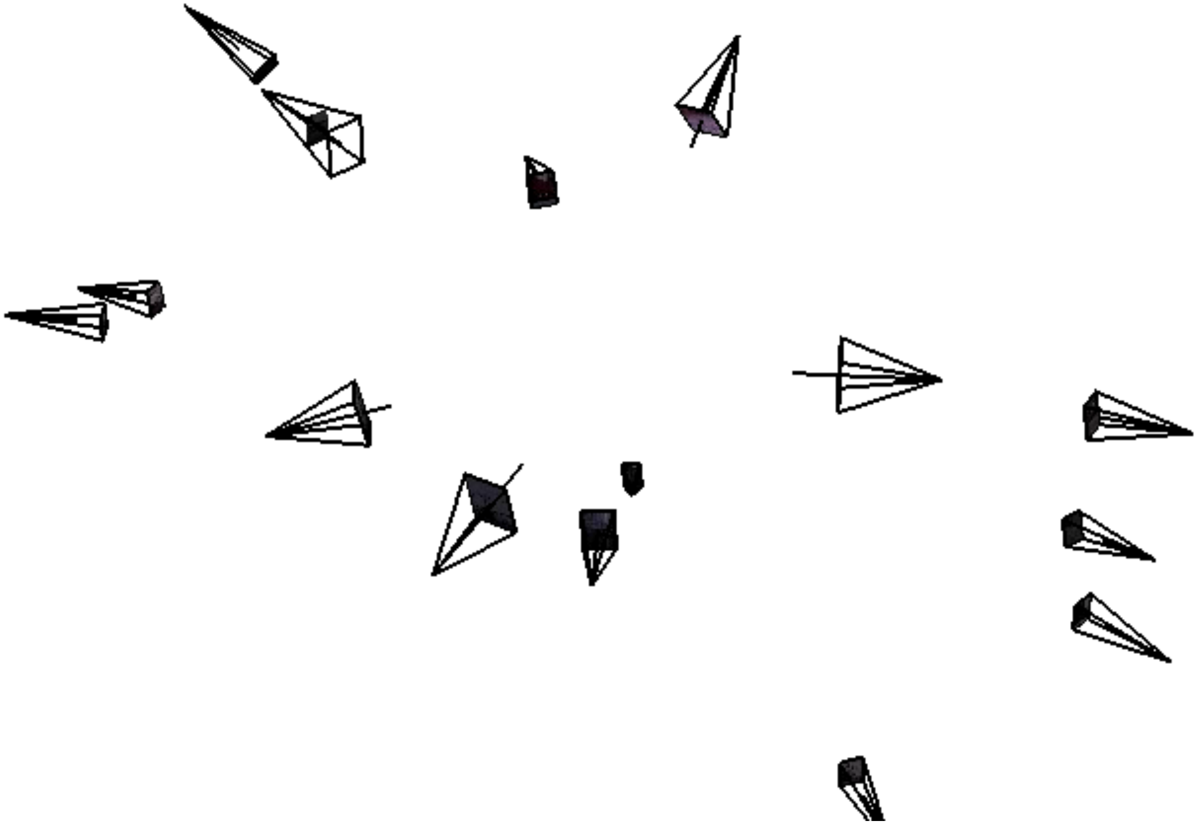


Camera tracking

VRML model

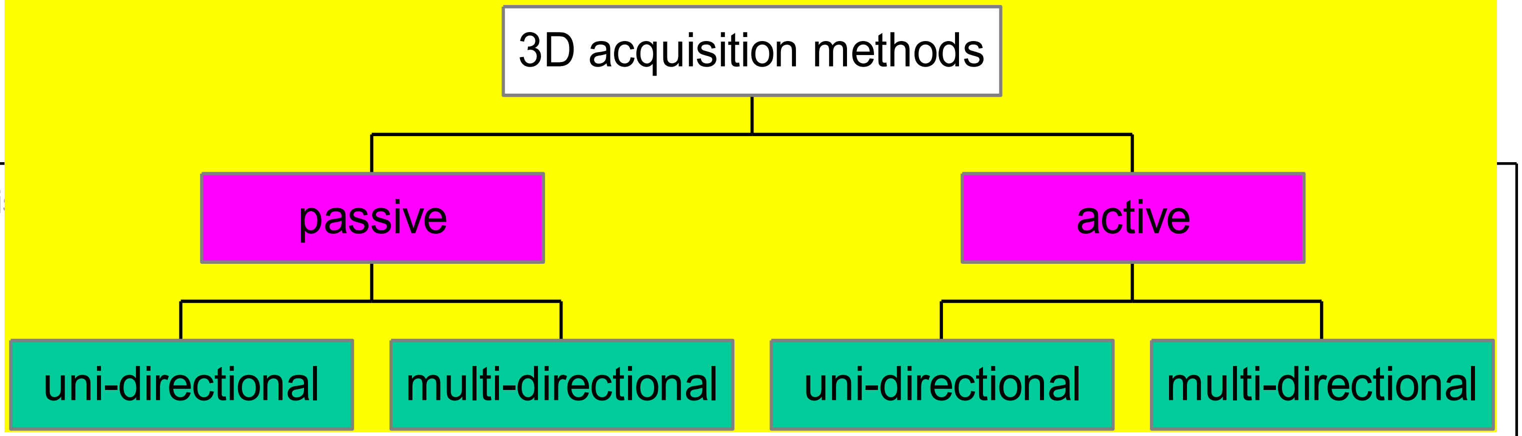
Outdoor visual hulls

Outdoor visual hulls



Computer Vision

3D acquisition taxonomy



Shape-from
- **texture**
- **contour**
- **silhouettes**
- **defocus**
- **shading**

Stereo

Time-of-flight

Line scanning

Structured light

Photom. stereo

REAL-TIME
FOCUS RANGE SENSOR

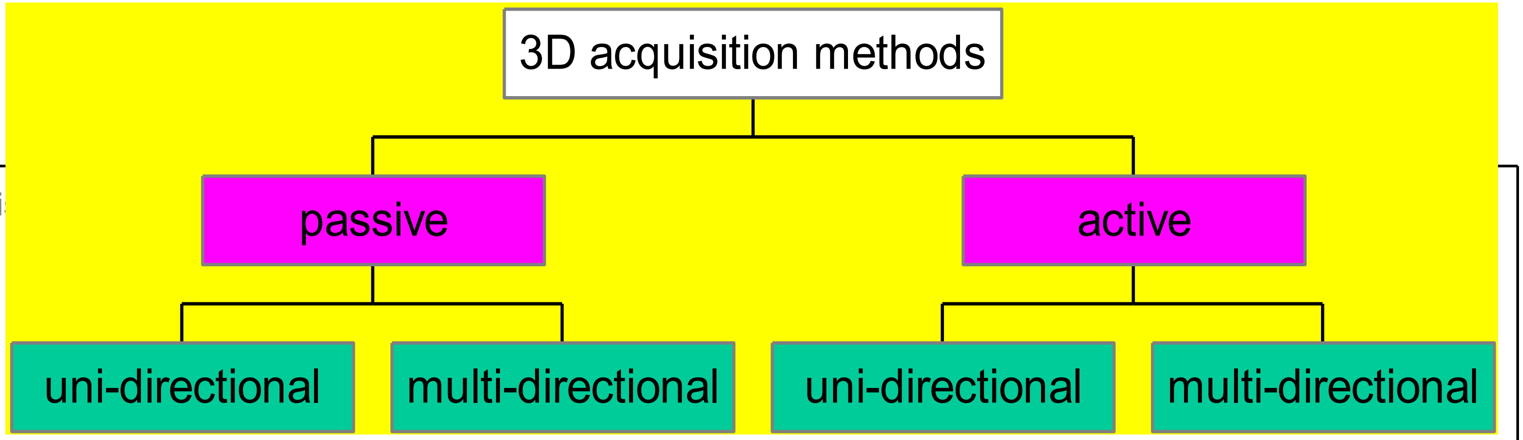
SHREE K. NAYAR

MASAHIRO WATANABE

MINORI NOGUCHI

COLUMBIA UNIVERSITY

3D acquisition taxonomy



Shape-from
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Stereo

Time-of-flight

Line scanning

Structured light

Photom. stereo

Shape-from-shading

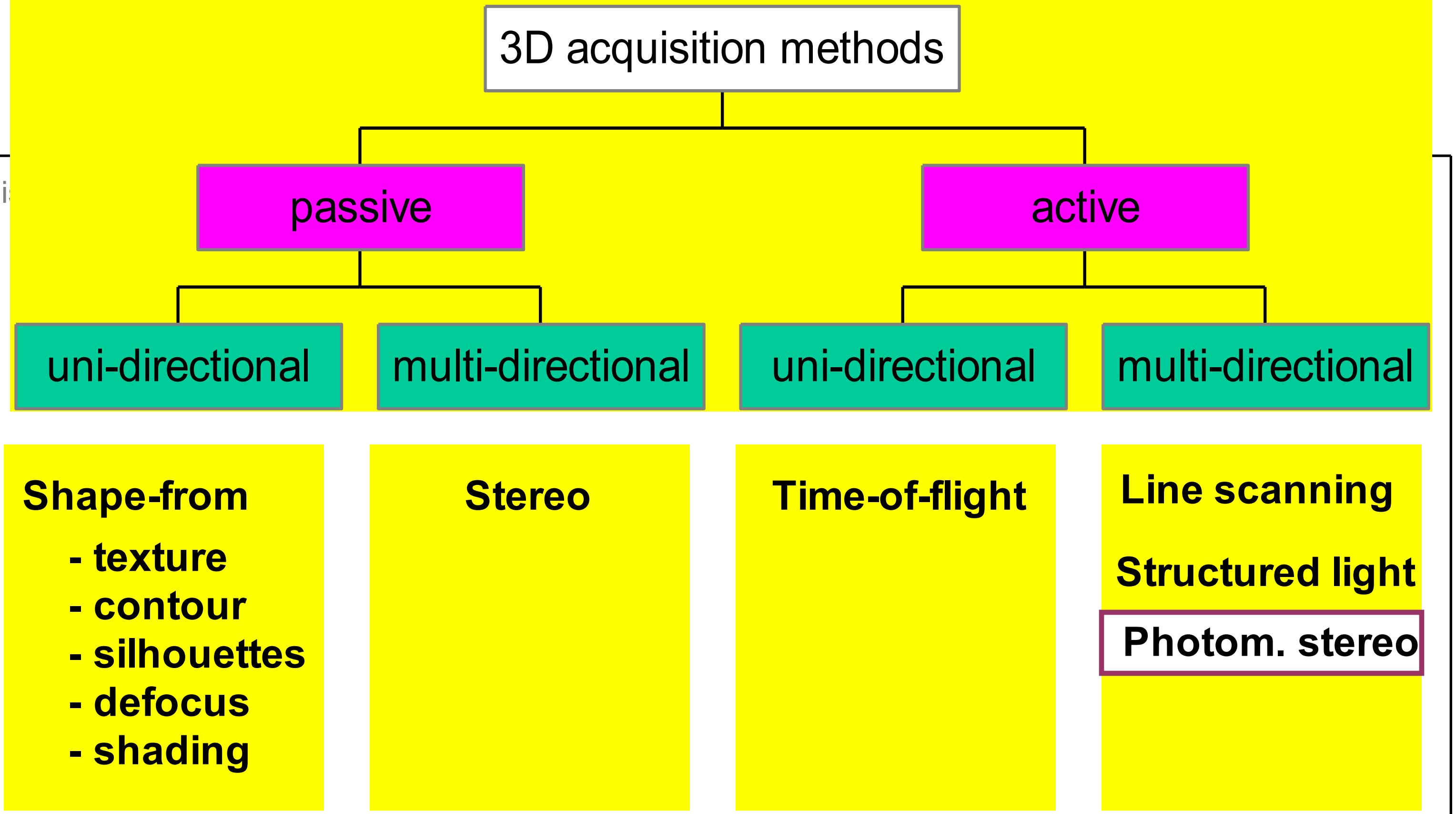
Uses directional lighting, often with known direction

local intensity is brought into correspondence with orientation via *reflectance maps*

orientation of an isolated patch cannot be derived uniquely

extra assumptions on surface smoothness and known normals at the rim

3D acquisition taxonomy



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- active
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Shape-from

- **- texture**
- **- contour**
- **- silhouettes**
- **- defocus**
- **- shading**

Stereo

Time-of-flight

Line scanning

Structured light

Photom. stereo

Photometric stereo

constraint propagation eliminated by using light from different directions

simultaneously when the light sources are given different colours

➔

Mini-dome for photometric stereo

Instead of working with multi-directional light applied simultaneously with the colour trick, one can also project from many directions in sequence…

Mini-dome for photometric stereo

KATHOLIEKE UNIVERSITEIT
LEUVEN

Mini-dome

Computer

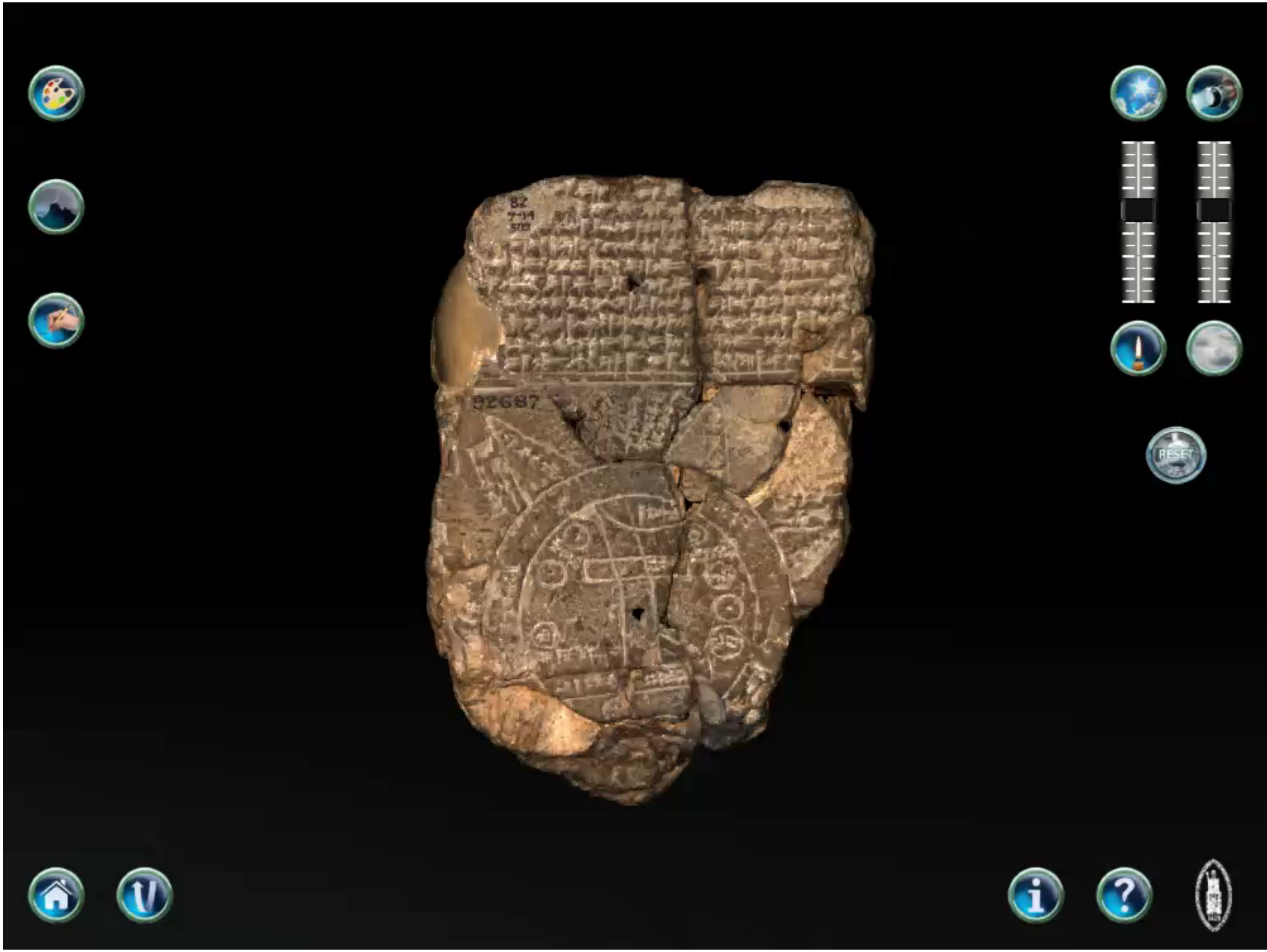
Mini-dome

Mini-dome for photometric stereo

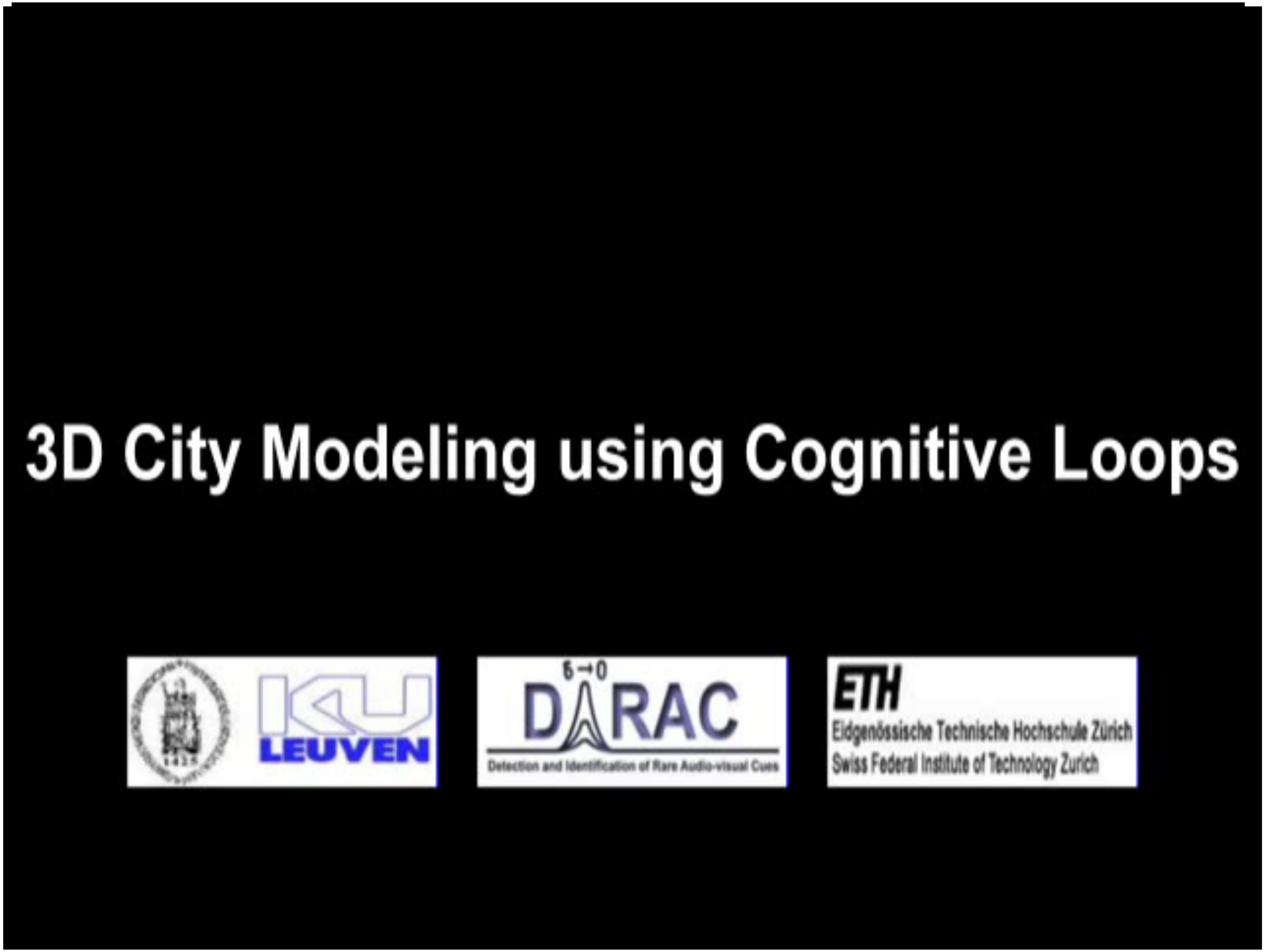
Example for tablet with first world map known, an exhibit at the British Museum:

http://homes.esat.kuleuven.be/~mproesma/mptmp/cuneiform

Mini-dome for photometric stereo



3D and recognition integrated



3D City Modeling using Cognitive Loops

KU LEUVEN

DIRAC

Detection and Identification of Rare Audio-visual Cues

ETH

Eidgenössische Technische Hochschule Zürich

Swiss Federal Institute of Technology Zurich

Multi-walker tracker

Strongest 3D cues for us are 2D...