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
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Stereo

The underlying principle is “triangulation”:
(Passive) stereo

1. A simple configuration
(Passive) stereo

Simple configuration:

- Two cameras with a baseline distance $b$.
- Focal length $f$.
- Correspondence points $(X,Y,Z)$ in 3D space.
- Image coordinates $(x_l, y_l)$ for the left camera and $(x_r, y_r)$ for the right camera.
A simple stereo setup

- identical cameras
- coplanar image planes
- aligned x-axes
A simple stereo setup

Reminder:

the camera projection can be formulated as

$$\rho p = KR^t (P - C)$$

for some non-zero $$\rho \in \mathbb{R}$$

Here $$R$$ is the identity...
A simple stereo setup

\[ \rho \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = K \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \]

\[ \rho' \begin{pmatrix} x' \\ y' \\ 1 \end{pmatrix} = K \begin{pmatrix} X - b \\ Y \\ Z \end{pmatrix} \]

\[ K = \begin{pmatrix} f k_x & 0 & 0 \\ 0 & f k_y & 0 \\ 0 & 0 & 1 \end{pmatrix} \]
A simple stereo setup

\[
\begin{align*}
\begin{aligned}
x &= \frac{f k_x X}{Z}, \\
y &= \frac{f k_y Y}{Z},
\end{aligned}
\quad \text{and} \quad \\
\begin{aligned}
x' &= \frac{f k_x (X - b)}{Z}, \\
y' &= \frac{f k_y Y}{Z},
\end{aligned}
\end{align*}
\]

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 \textit{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
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 $\pm 10$ 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...
Computer Vision
(Passive) stereo

II. General configuration
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:

![Diagram of stereo setup](image)
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

\[ P = C + \mu R K^{-1} p \quad \text{for some } \mu \in \mathbb{R} \]
Stereo, the general setup

so, the ray is given by

\[ P = C + \mu RK^{-1} p \quad \text{for some} \quad \mu \in \mathbb{R} \]

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

\[ \rho' p' = \mu K'R'^t RK^{-1} p + K'R'^t (C - C') \]
Stereo, the general setup

the projected ray was found to be

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

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

\[ \rho' e' = K'R'^t (C - C') \]

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

finally, adopting the simplifying notation

\[ A = \frac{1}{\rho'_e} K'R'^t RK^{-1} \]

\[ \rho'^p' = \rho'_e (\mu Ap + e') \]

\( A \) is the **infinity homography**
Stereo, the general setup

note that the epipole lies on all the epipolar lines
Stereo, the general setup

\[ \rho'p' = \rho'_e (\mu Ap + e') \]

the epipolar constraint (epipolar line)

we can rewrite this constraint as

\[ |p'e'Ap| = p''^t (e' \times Ap) = 0 \]
Stereo, the general setup

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

can be written, given

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

as

\[ |p' e' A p| = p''^t [e']_x A p \]

\[ F = [e']_x A \] is the \textit{fundamental matrix}.

\[ F \] has rank 2
Stereo, the general setup

\[ p^{''t} \left[ e' \right] \times Ap = 0 \rightarrow p^{''t} F p = 0 \]
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 $p, p', \text{and } p''$
$p''$ is found at the intersection of epipolar lines:

fails when the epipolar lines coincide

$\Rightarrow$ trifocal constraints
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 \( \mu, \mu' \)

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

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

Points and cameras → Tracking and Calibration → Dense depth estimation → 3D surface modeling

Depth map

3D models
Uncalibrated reconstruction
Uncalibrated reconstruction - example

Univ. of Leuven
Input Images
shots taken with Canon EOS D60
(Resolution: 6.3 Megapixel)
Shape-from-stills

www.arc3d.be

Webservice, free for non-commercial use
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Active triangulation

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

LASER SPOT SEEN BY THE CAMERA

CAMERA’S CENTER OF PROJECTION
Active triangulation

LASER

LASER SPOT SEEN BY THE CAMERA

CAMERA'S CENTER OF PROJECTION

NO INTERSECTION IF SOME ERRORS IN THE LINE EQS!
Active triangulation

Two lines do normally not intersect...
Noise disrupts triangulation

LASER SPOT SEEN BY THE CAMERA

CAMERA’S CENTER OF PROJECTION

NO INTERSECTION IF SOME ERRORS IN THE LINE EQS!
Active triangulation

- Laser with cylindrical lens in front
- Intersection laser plane & viewing ray
- Intersection laser plane & object surface
- 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

Camera image
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
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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:

1 projector

2 camera
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
Computer Vision

Shape + texture often needed

Higher resolution

Texture is also extracted
Computer Vision

Lara Croft
Thomb Raider

James Bond
Die another day
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.
Kinect: 9x9 patches with locally unique code
Kinect as one-shot, low-cost scanner

Excerpt from the dense NIR dot pattern:

Face animation - input
Face animation – replay + effects
Facial motion capture
motion capture for *League of Extraordinary Gentlemen*
Facial motion capture
Phase shift

projector
color wheel
high-speed cameras
texture camera
Phase shift

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

\[ I_r = A + R \cos (\phi - \theta) \]
\[ I_g = A + R \cos (\phi) \]
\[ I_b = A + R \cos (\phi + \theta) \]
Phase shift

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

$$\phi = \arctan \left( \frac{\tan \left( \frac{\theta}{2} \right) \frac{I_r - I_b}{2I_g - I_r - I_b} }{ } \right)$$
4D acquisition

Motion retargetting, from 3D phase shift scans

Face/Off: Live Facial Puppetry

PaperID 102
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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

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

Distance = \( C \times \frac{\Delta T}{2} \)
Laser sweeps over surface

800 pts/sec

2mm min pt-to-pt spacing

40° x 40°
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
Step 2:
Scan the structure
Step 3:
Color the points
Step 4: Model fitting in-the-field
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

Man-hours

Cyrax Manual

544 892

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

3-D Reconstruction based on Multi-View Stereo

LIDAR Measurements

Image courtesy of Tippett Studio
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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
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Shape-from-contour

makes assumptions about contour shape

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

\[ \downarrow \]

ellipse \( \rightarrow \) circle

E.g. assumption of symmetry

\[ \downarrow \]

Symmetric contours \( \rightarrow \) surface of revolution
Shape-from-contour
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Shape-from-silhouettes
Shape from silhouettes - uncalibrated

- tracking of turntable rotation
  - volumetric modeling from silhouettes
  - triangular textured surface mesh
Outdoor visual hulls
Outdoor visual hulls
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Real-Time
Focus Range Sensor

Shree K. Nayar
Masahiro Watanabe
Minori Noguchi
Columbia University
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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.
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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
Computer Vision

Mini-dome
Mini-dome