3D Scanning

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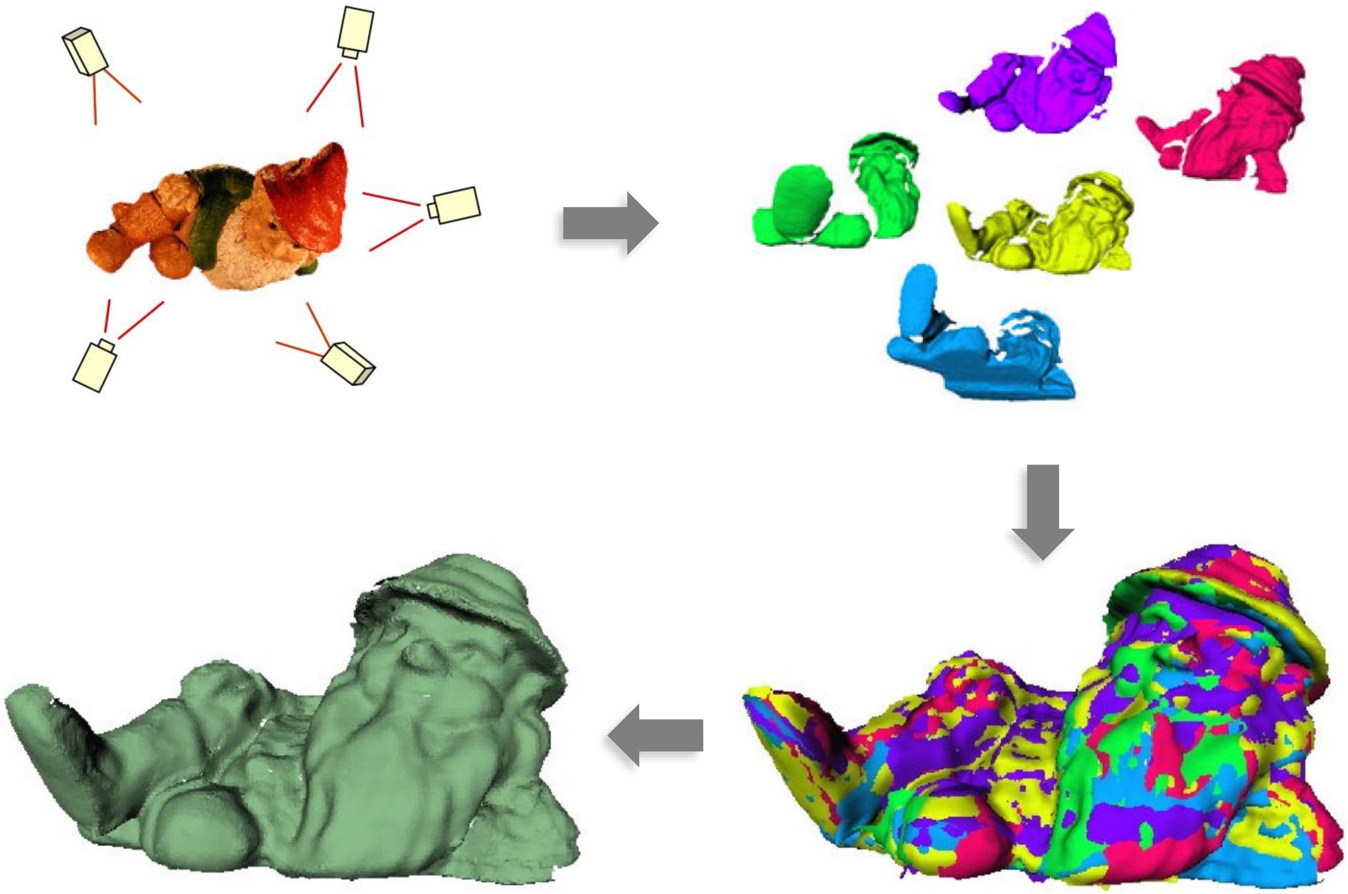
Slide Credit: Yasutaka Furukawa

Geometry Reconstruction Pipeline



This Lecture

Depth Sensing

ICP for Pair-wise Alignment

Next Lecture

Global Alignment

Pairwise

Multiple

Depth Sensing

- Range acquisition
  - Contact
    - Mechanical (CMM, jointed arm)
    - Inertial (gyroscope, accelerometer)
    - Ultrasonic trackers
    - Magnetic trackers
  - Transmissive
    - Industrial CT
    - Ultrasound
    - MRI
  - Reflective
    - Non-optical
      - Radar
      - Sonar
    - Optical

Slide credit: Szymon Rusinkiewicz

Touch Probes

- Jointed arms with angular encoders
- Return position, orientation of tip

Faro Arm – Faro Technologies, Inc.

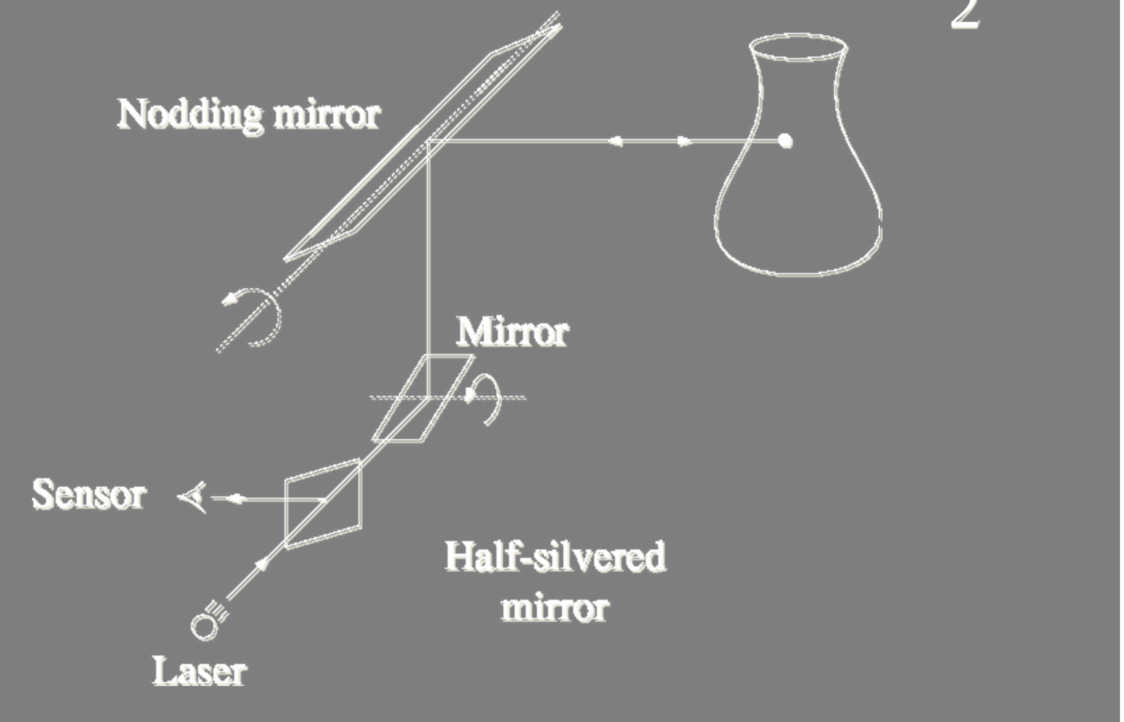
Depth Sensing

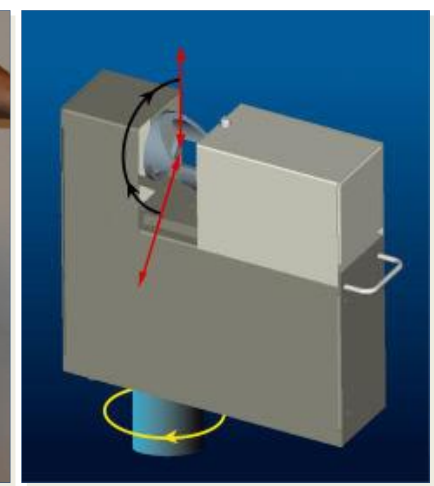
- Optical methods
  - Passive
    - Shape from X:
      - stereo
      - motion
      - shading
      - texture
      - focus
      - defocus
  - Active
    - Active variants of passive methods
      - Stereo w. projected texture
      - Active depth from defocus
      - Photometric stereo
    - Time of flight
    - Triangulation

Pulsed Time of Flight

- Basic idea: send out pulse of light (usually laser), time how long it takes to return

$$d = \frac{1}{2} c \Delta t$$





Pulsed Time of Flight

- Advantages:
  - Large working volume (up to 100 m.)
- Disadvantages:
  - Not-so-great accuracy (at best ~5 mm.)
    - Requires getting timing to ~30 picoseconds
- Often used for scanning buildings, rooms, archeological sites, etc.

AM Modulation Time of Flight

- Modulate a laser at frequency ν_m, it returns with a phase shift $\Delta\varphi$

$$d = \frac{1}{2}\left(\frac{c}{\nu_m}\right)\left(\frac{\Delta\varphi \pm 2\pi n}{2\pi}\right)$$

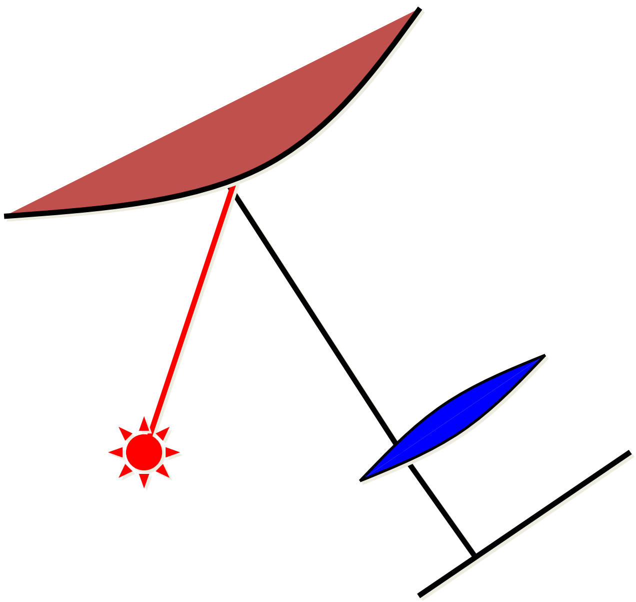
- Note the ambiguity in the measured phase!
$\Rightarrow$ Range ambiguity of ${}^1/_2\lambda_m n$

AM Modulation Time of Flight

- Accuracy / working volume tradeoff (e.g., noise ~ $^1/_{500}$ working volume)

- In practice, often used for room-sized environments (cheaper, more accurate than pulsed time of flight)

Triangulation

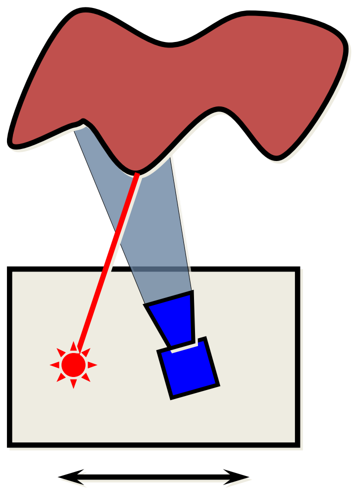


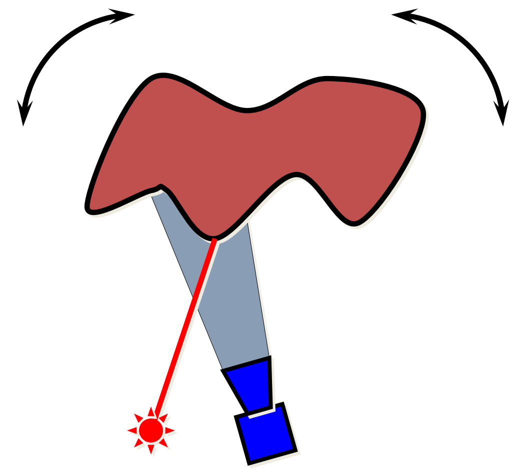
Triangulation: Moving the Camera and Illumination

- Moving independently leads to problems with focus, resolution

- Most scanners mount camera and light source rigidly, move them as a unit

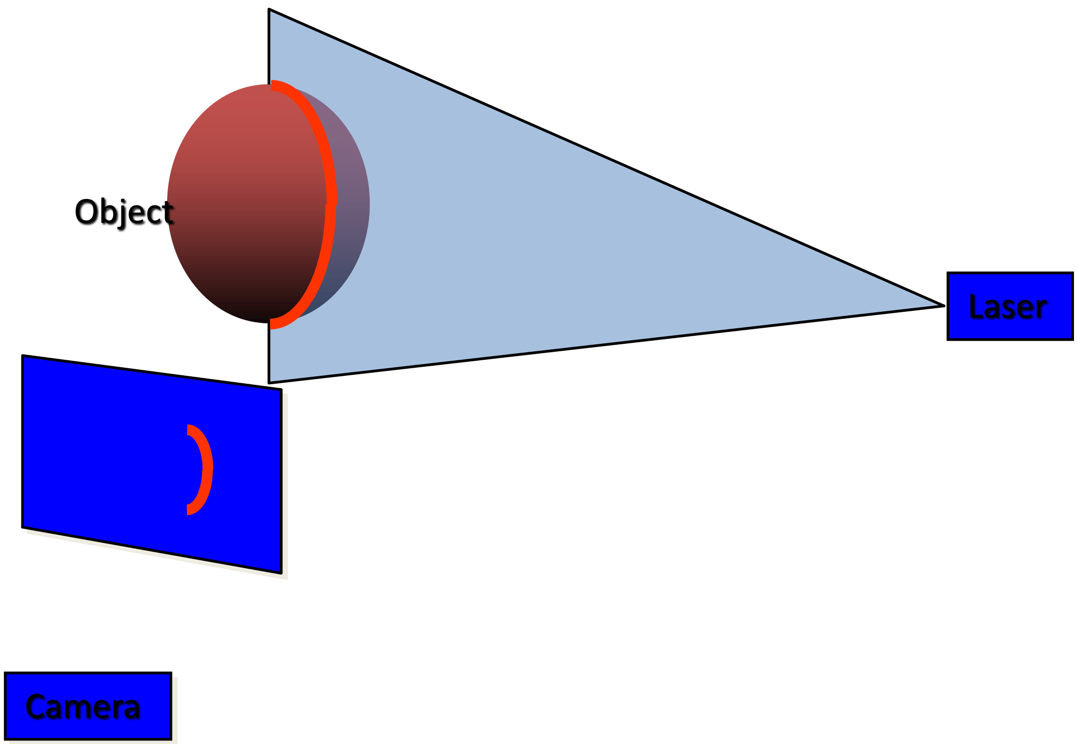
Triangulation: Moving the Camera and Illumination





Triangulation: Extending to 3D

- Possibility #1: add another mirror (flying spot)
- Possibility #2: project a stripe, not a dot



Pattern Design

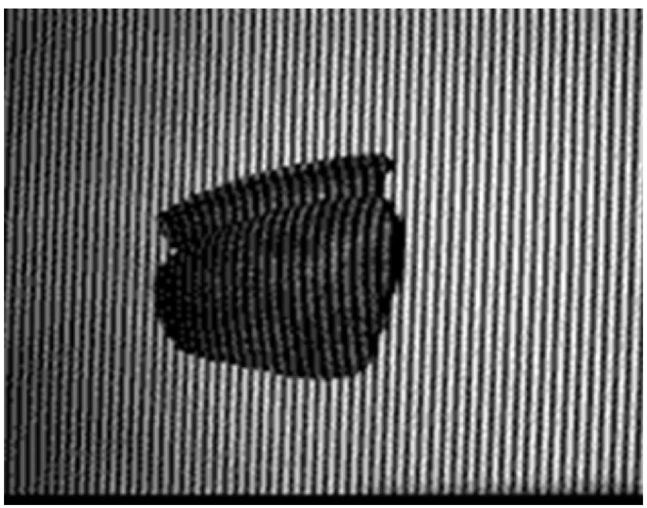
Structured Light General Principle

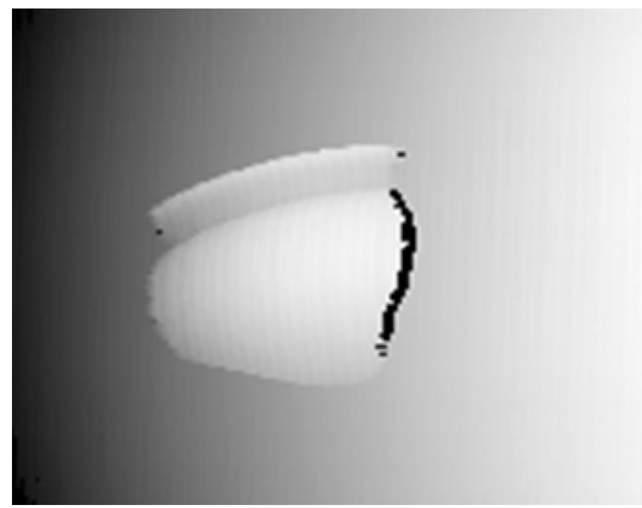
Zhang et al, 3DPVT (2002)

Project a known pattern onto the scene and
infer depth from the deformation of that pattern

Time-Coded Light Patterns

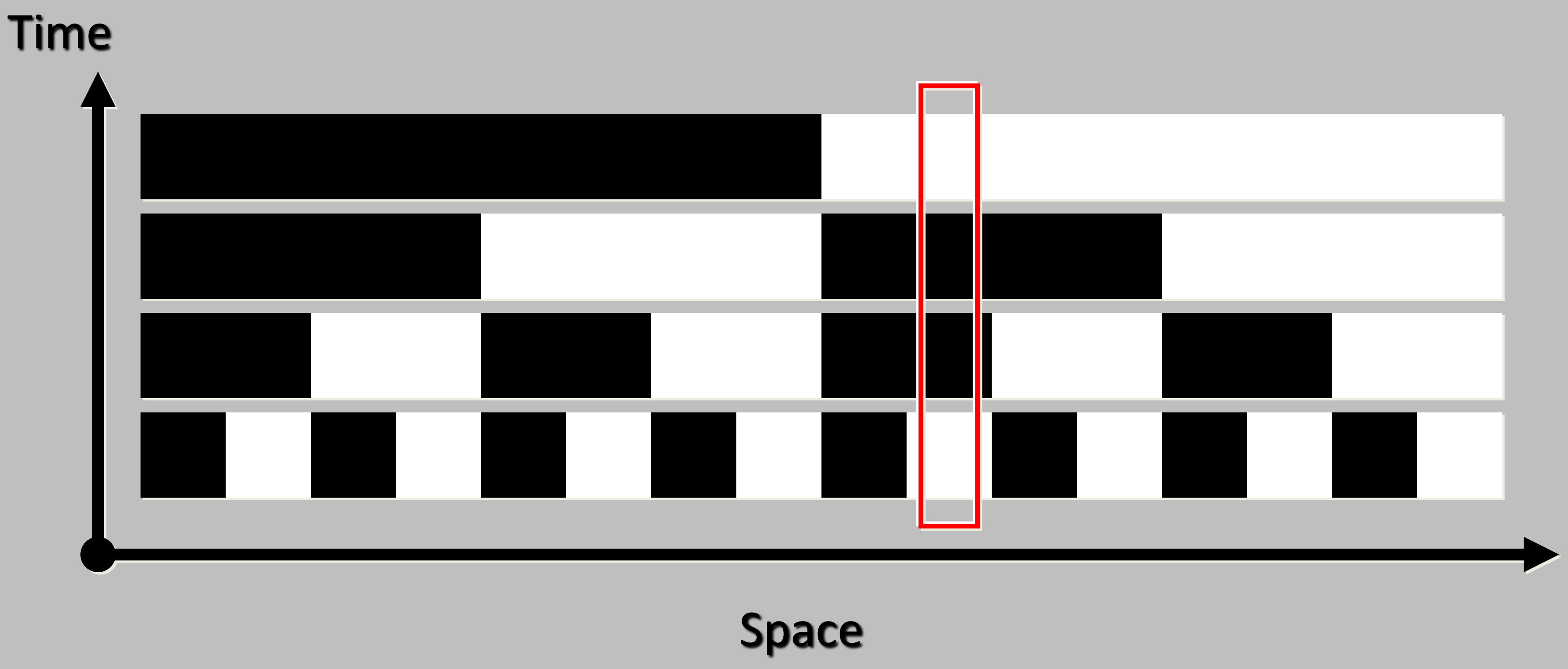
- Assign each stripe a unique illumination code over time [Posdamer 82]





Time-Coded Light Patterns

- Assign each stripe a unique illumination code over time [Posdamer 82]



Binary Encoded Light Stripes

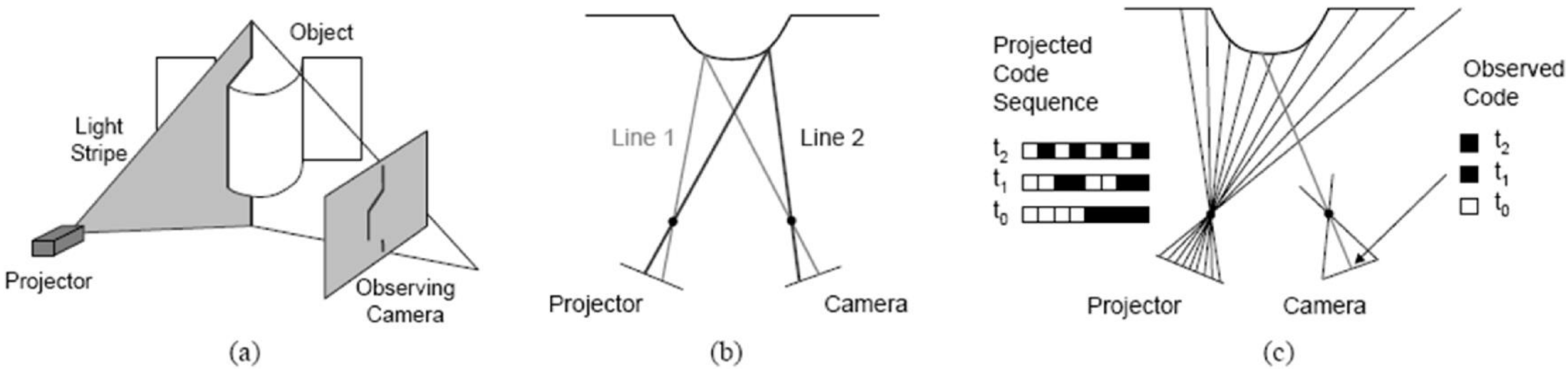
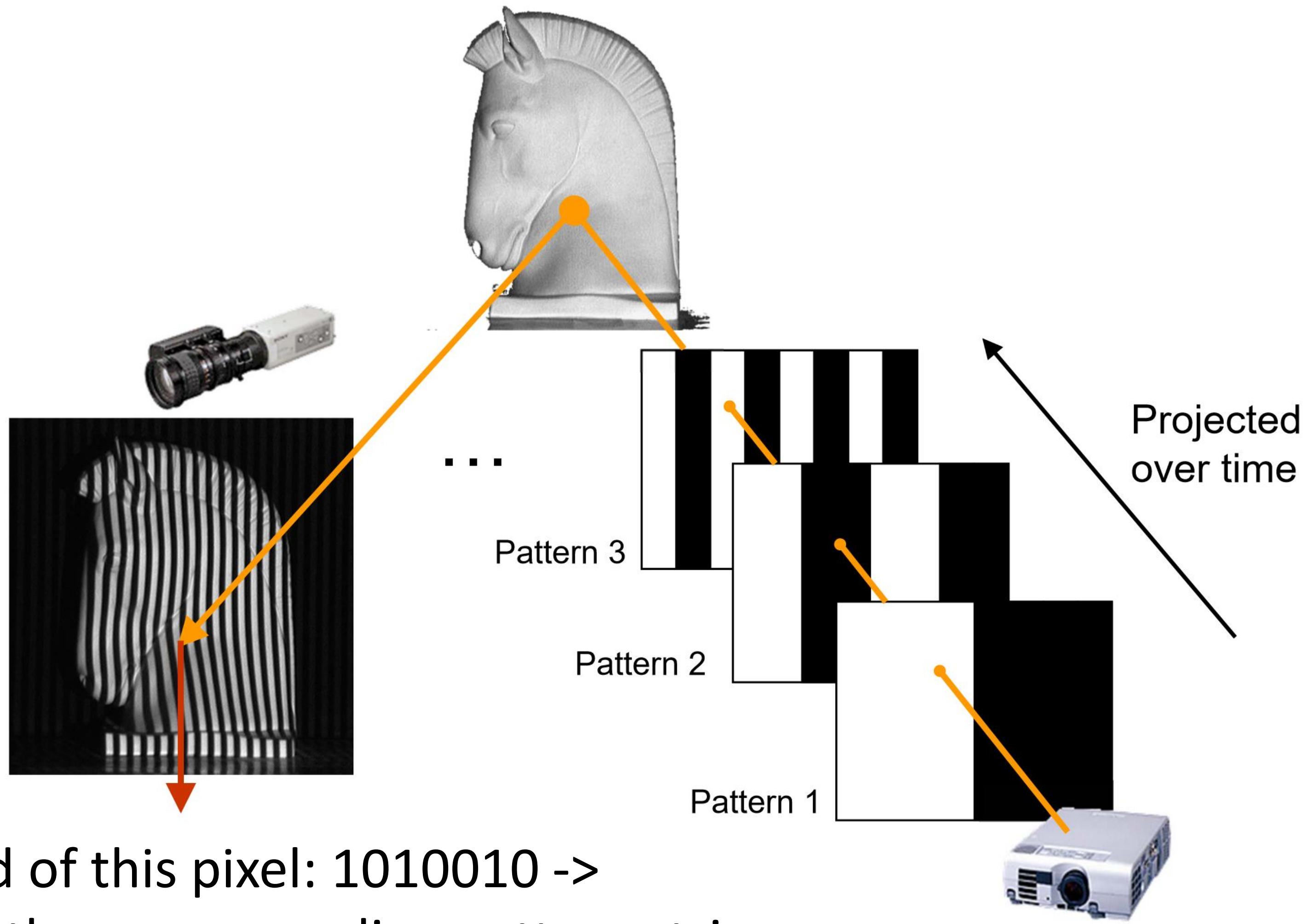


Figure 2. (a) Standard light sectioning with one light stripe. (b) Top view of light sectioning using more than one stripe. (c) Light sectioning using structured light.

- Set of light planes are projected into the scene
- Individual light planes are indexed by an encoding scheme for the light patterns
  - Obtained images are used to uniquely address the light plane corresponding to every image point

Binary Coding Example



Codeword of this pixel: 1010010 ->
Identifies the corresponding pattern stripe

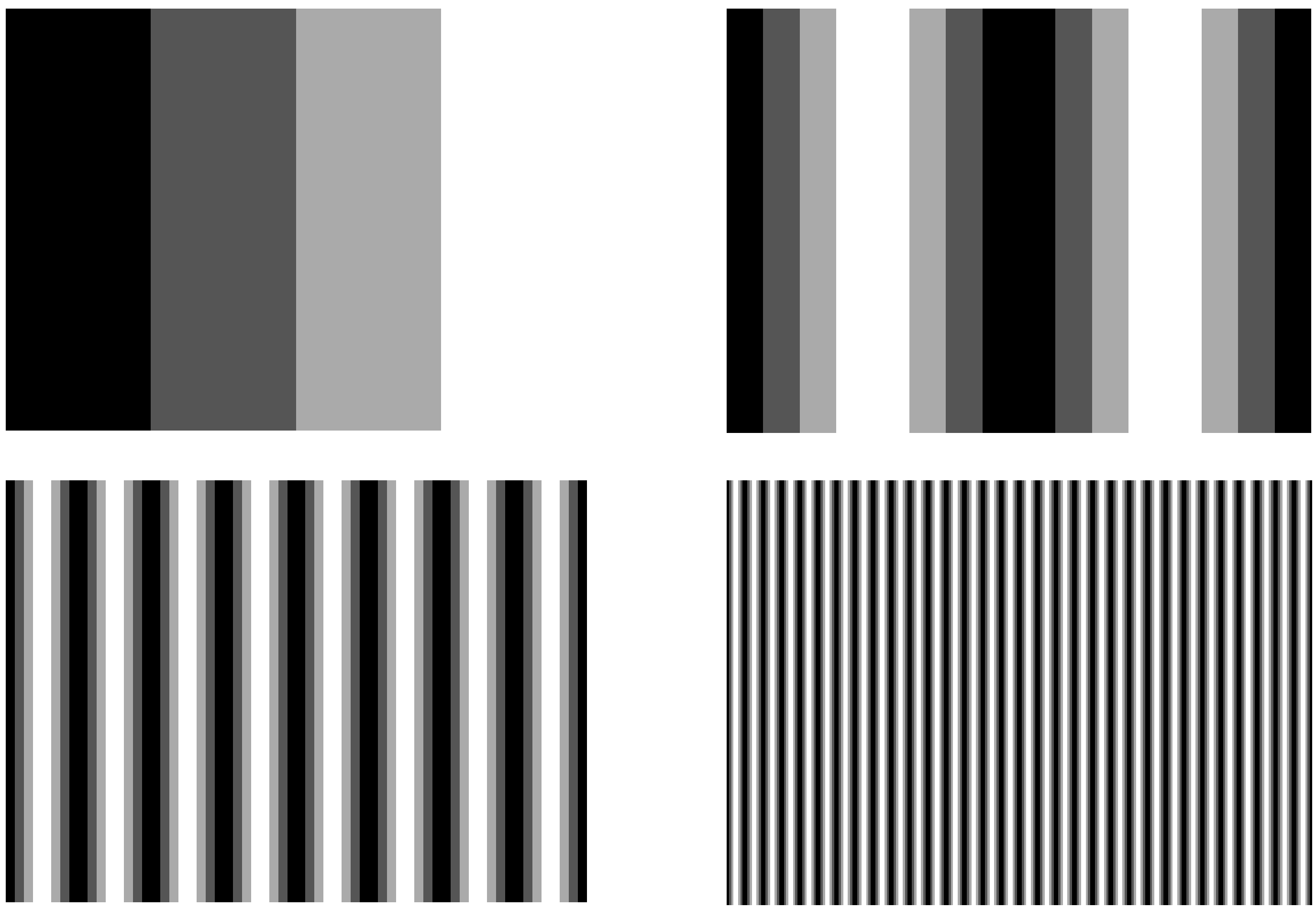
Accounting for Reflectance

- Because of surface reflectance and ambient light, distinguishing between black and white not always easy

- Solution: project all-white (and sometimes all-black) frame

- Permits multiple shades of gray

Multiple Shades of Gray



Multiple Shades of Gray



Temporal vs. Spatial Continuity

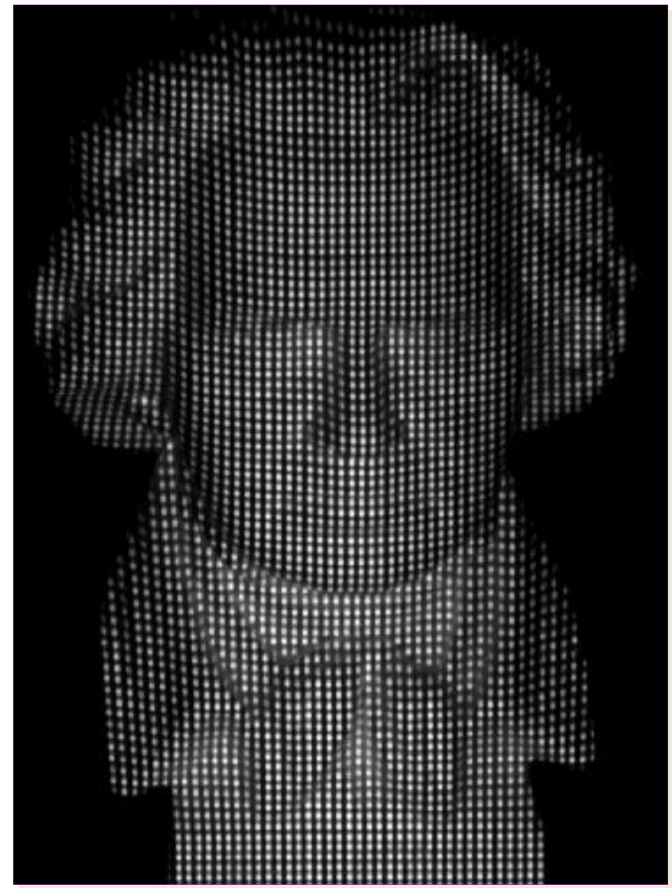
- Structured-light systems make certain assumptions about the scene:

- Temporal continuity assumption:
  - Assume scene is static
  - Assign stripes a code over time

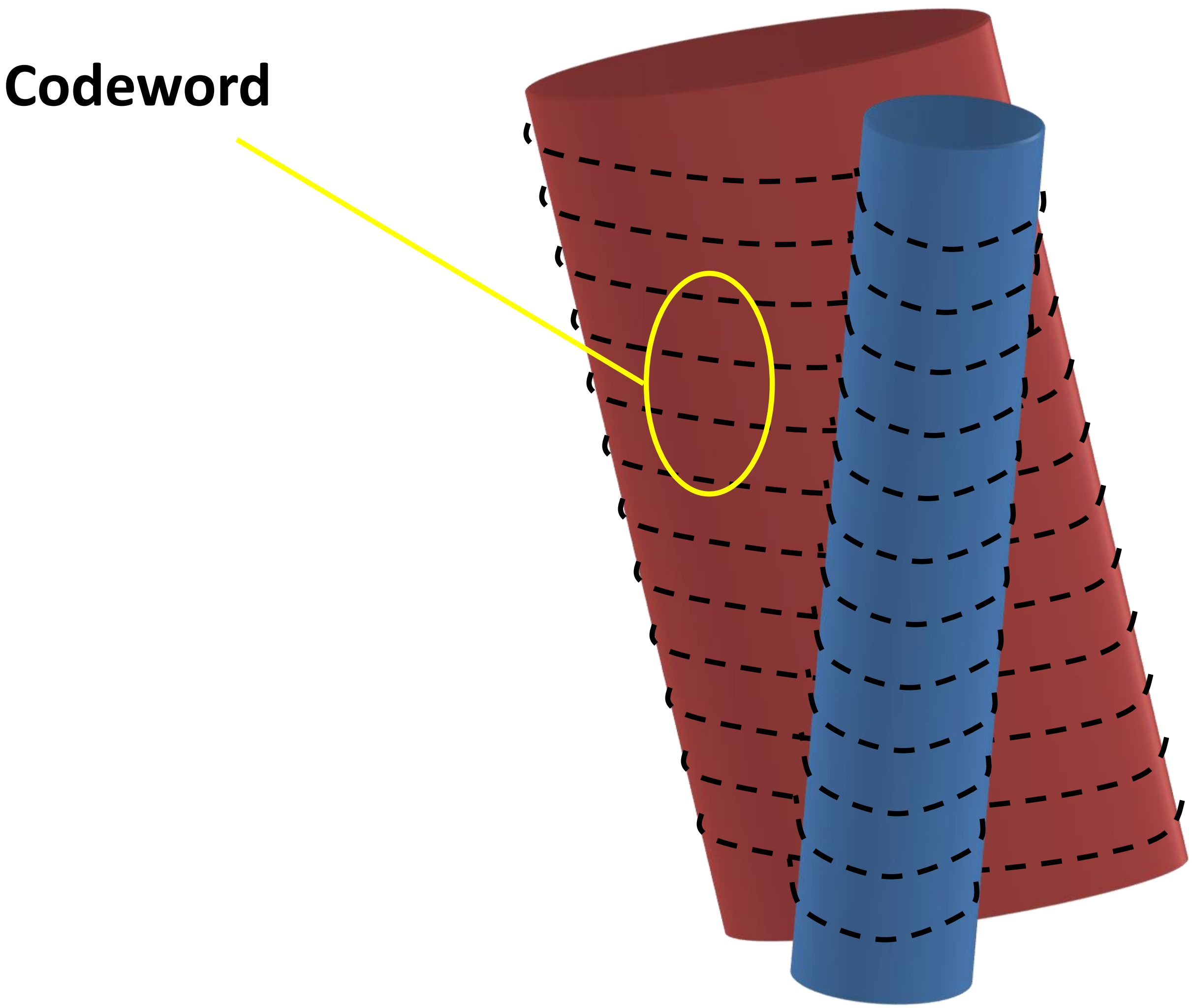
- Spatial continuity assumption:
  - Assume scene is one object
  - Project a grid, pattern of dots, etc.

Grid Methods

- Assume exactly one continuous surface
- Count dots or grid lines
- Occlusions cause problems
- Some methods use dynamic programming

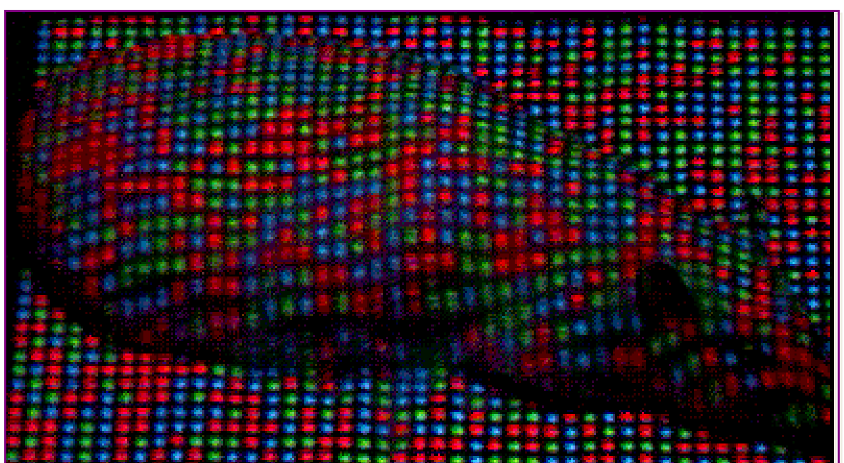


Codes Assuming Local Spatial Continuity



Codes Assuming Local Spatial Continuity

[Zhang et al. 02]



[Ozturk et al. 03]

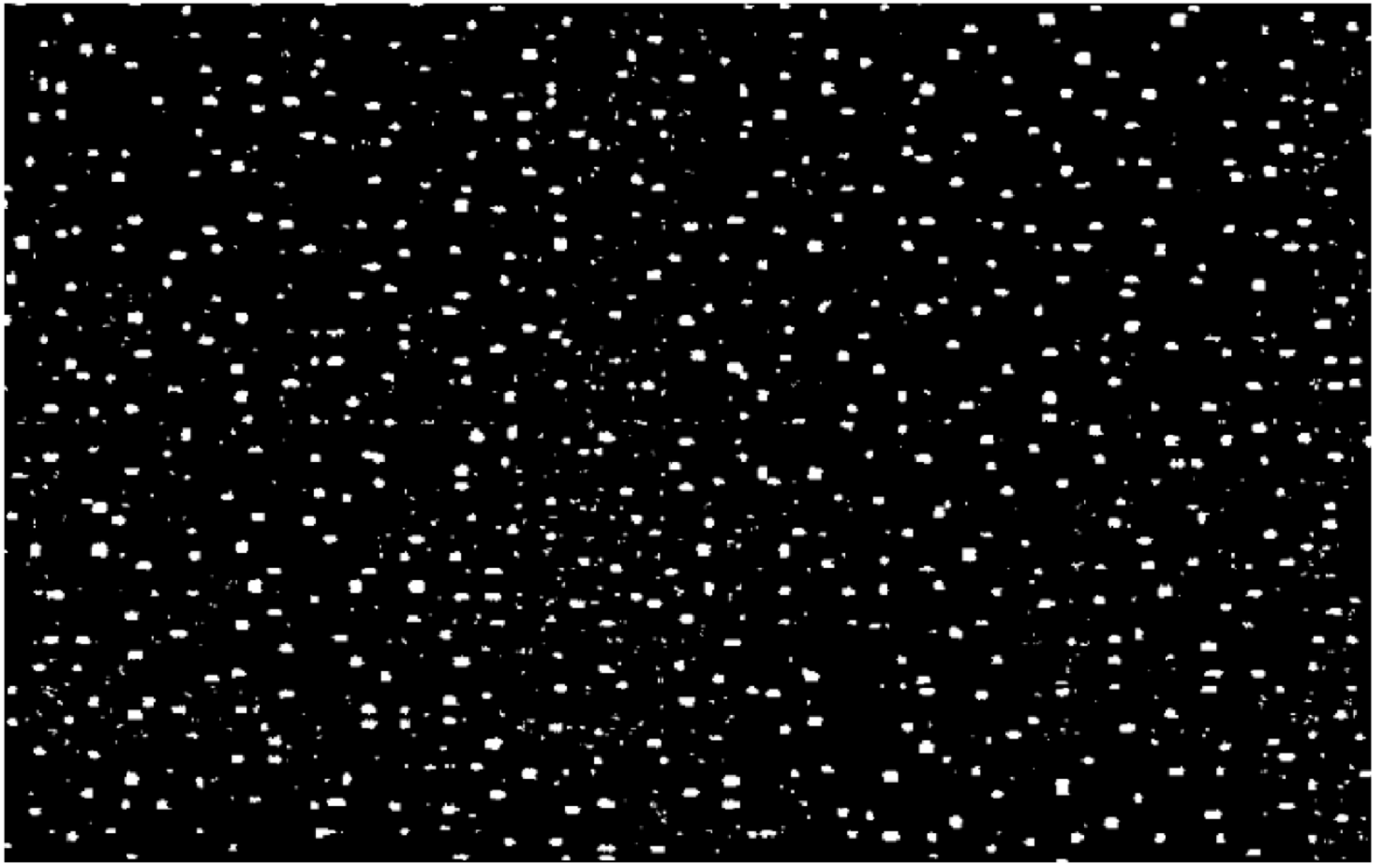
Homework: How to handle moving objects?

Kinect

Kinect combines structured light with two classic computer vision techniques: depth from focus, and depth from stereo

Figure copied from Kinect for Windows SDK Quickstarts

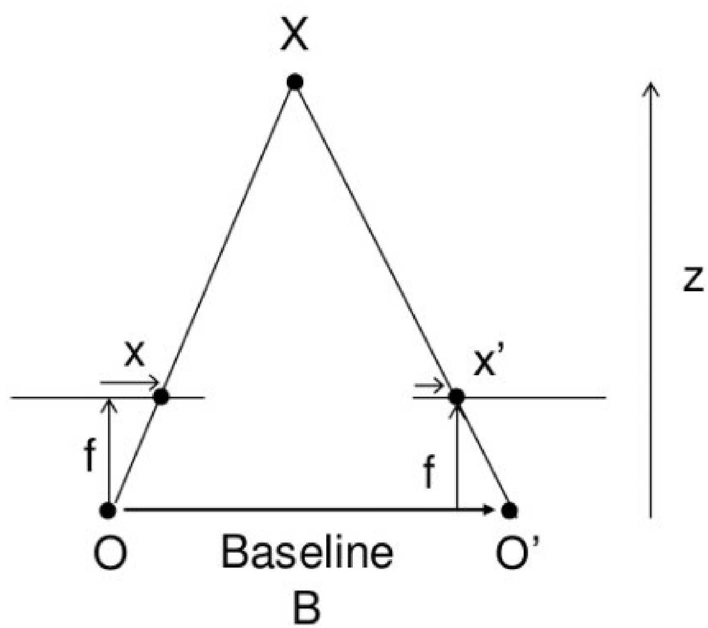
The Kinect uses infrared laser light, with a speckle pattern



Shpunt et al, PrimeSense patent application
US 2008/0106746

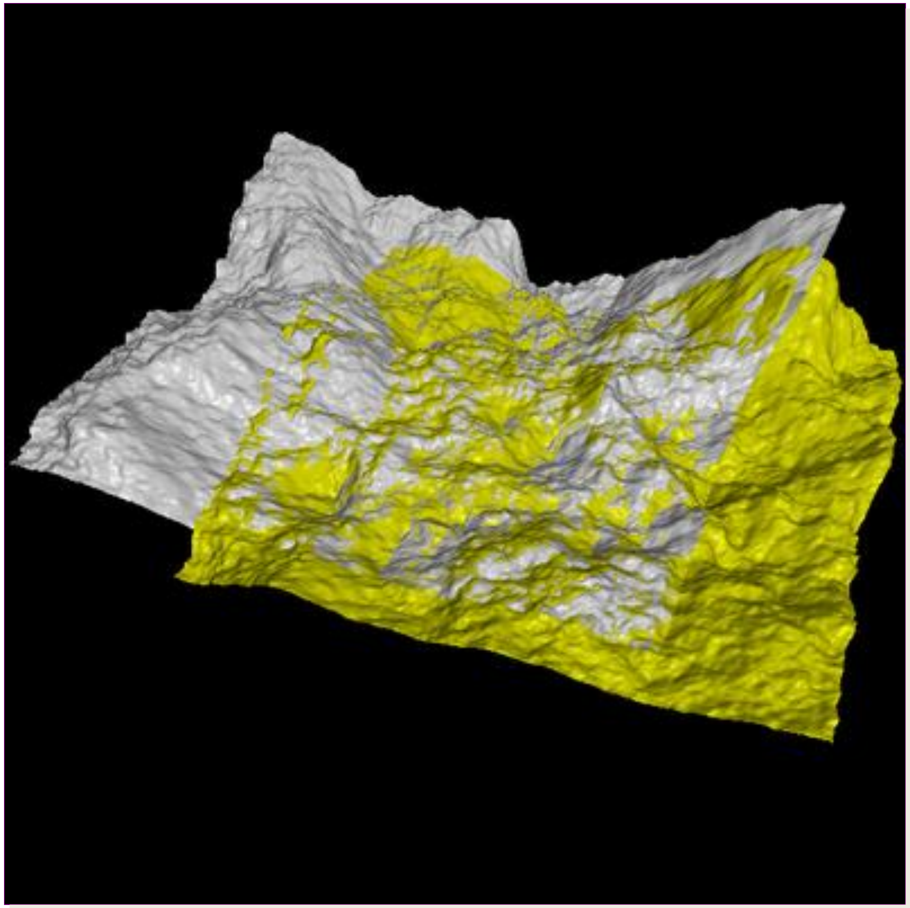
Depth from Stereo Uses Parallax

- The Kinect analyzes the shift of the speckle pattern by projecting from one location and observing from another



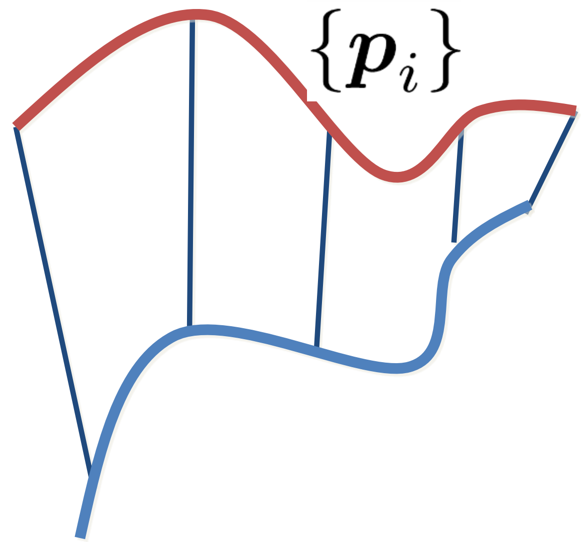
ICP for Pairwise Alignment

Pairwise Alignment



ICP
[Besel and Mckay' 92]

ICP Formulation



$$\underset{R,\boldsymbol{t}}{\text{minimize}} \quad \sum_{i=1}^{n} d^2(R(\boldsymbol{p}_i) + \boldsymbol{t}, T)$$

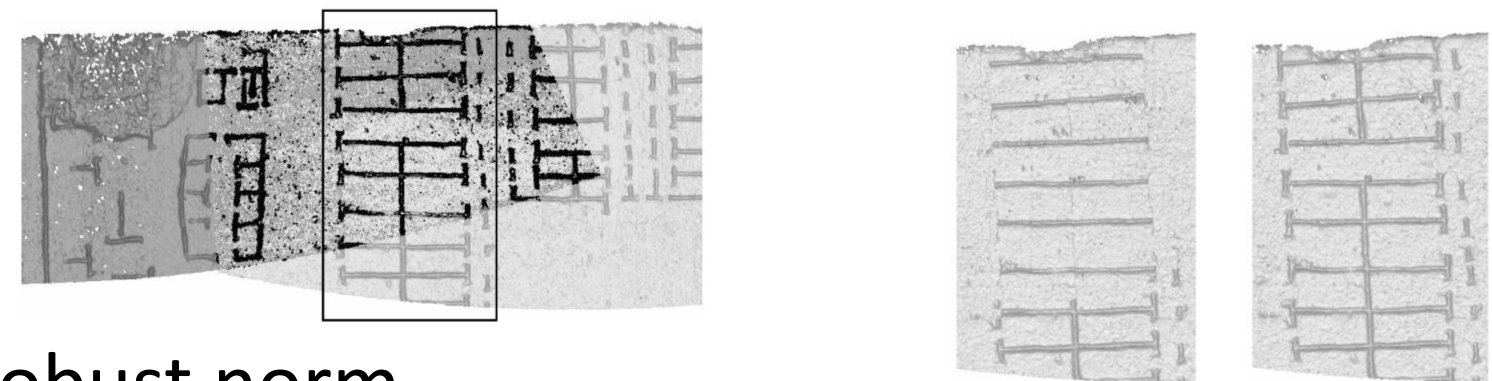
$$\underset{R,\boldsymbol{t}}{\text{minimize}} \quad \sum_{i=1}^{n} \min_{\boldsymbol{q}\in T} \ \|R(\boldsymbol{p}_i) + \boldsymbol{t} - \boldsymbol{q}\|^2$$

ICP Variants

- Point-plane distance [Chen and Medioni' 91]

$$\underset{R,\boldsymbol{t}}{\text{minimize}} \quad \sum_{i=1}^{n} \left((R\boldsymbol{p}_i + \boldsymbol{t} - \boldsymbol{q}_i)^T \boldsymbol{n}_i\right)^2$$

- Stable sampling [Gelfand et al. 03]



- Robust norm

$$\underset{R,\boldsymbol{t}}{\text{minimize}} \quad \sum_{i=1}^{n} \min_{\boldsymbol{q}\in T} \|R(\boldsymbol{p}_i) + \boldsymbol{t} - \boldsymbol{q}\|$$