Computer Vision

(Summer Semester 2023)

Lecture 10

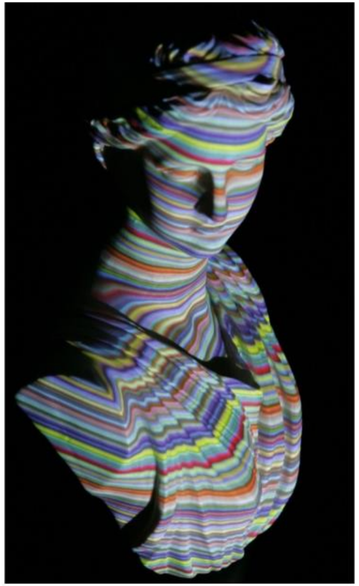
Structured Light

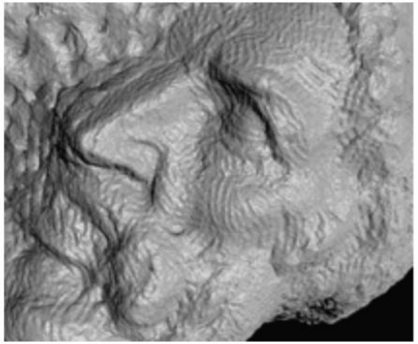
- Slides based on
  - Szeliski’s book “Computer Vision: Algorithms and Applications”: http://szeliski.org/Book/
  - Slides from Computer Vision lectures of: Marc Stamminger / Christian Riess (2018) and Elli Angelopoulou (2014)

Up to now: Passive Image Acquisition

Left Image **Right Image** **Reconstruction**

Today: Active Image Acquisition





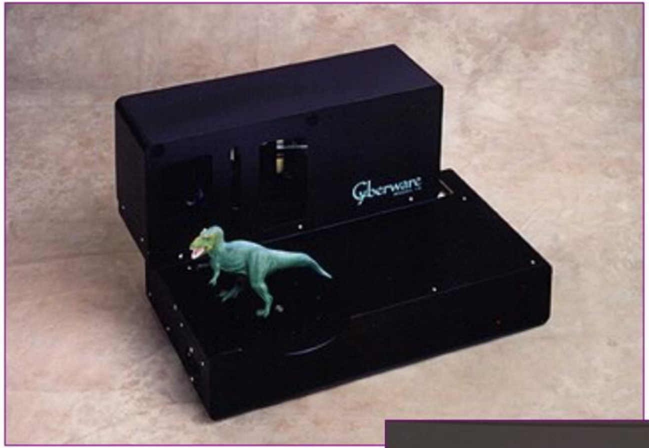
Passive – Active Image Acquisition

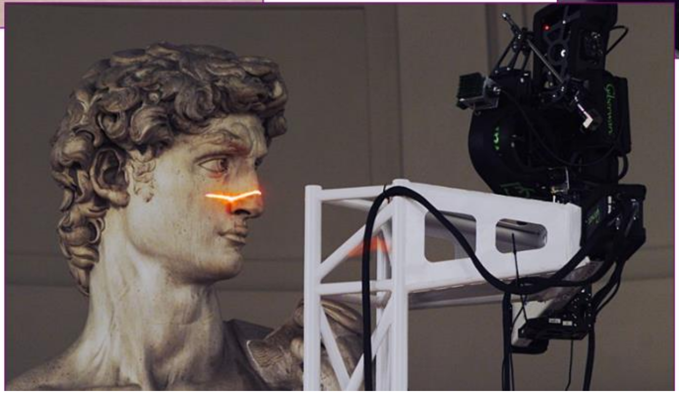
- Passive image acquisition:
  - just take two pictures, find correspondences
  - difficult, if no correspondences can be found (white wall example)

- Active image acquisition **I**:
  - add a projector that generates a pattern that helps to find correspondences

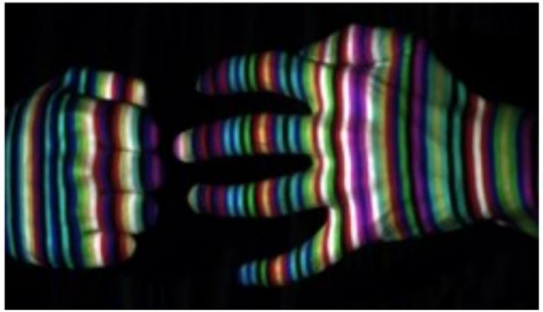
- Active image acquisition **II**:
  - replace one camera by a projector
  - use projector image as one of the two images to find correspondences

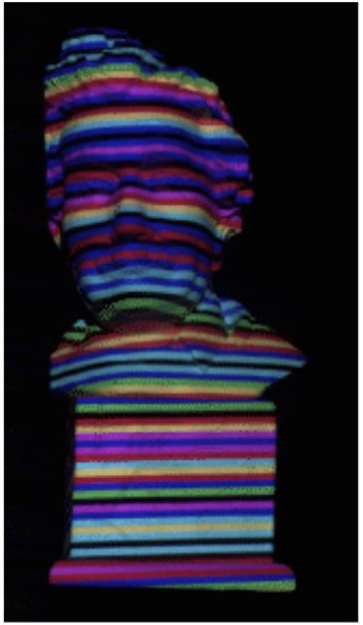
Active Image Acquisition - Laser Scanning





Active Image Acquisition - Structured Light





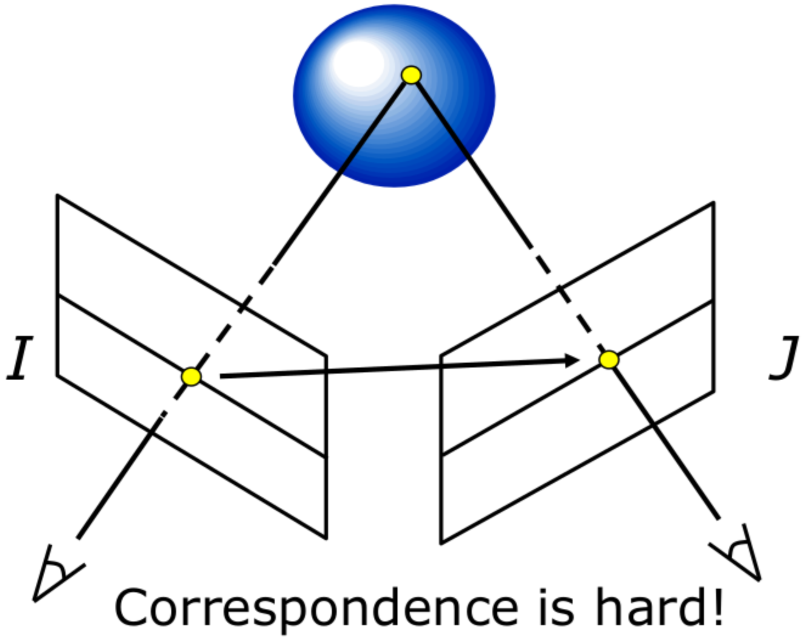
Passive *vs.* Active Acquisition

- **Passive (stereo, motion)**
  - Easy data collection (just take pictures).
  - Non-intrusive setup.
  - Can produce dense depth maps.
  - May not work for featureless surfaces.

- **Active (range scanning, ToF, structured light)**
  - More robust correspondence.
  - Can recover data even at featureless parts of the scene.
  - Higher accuracy but possibly sparser depth maps.
  - Very popular in industrial setups
  - More complex data hardware.
  - Intrusive (active illumination may alter scene appearance)
  - Limited range of depth.

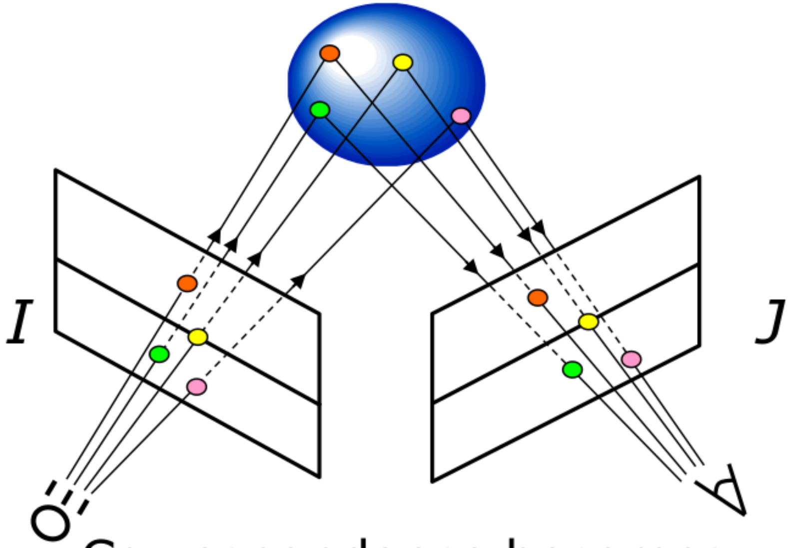
Stereo Triangulation

- In traditional stereo, correspondence can be quite challenging.
- For each pixel in one image, we look for corresponding pixel in the other image.
- **Typical method:** Look for pixels on the conjugate epipolar line choose the pixel with most similar value. This is often done in an error (dissimilarity) minimization framework .



Structured Light Triangulation

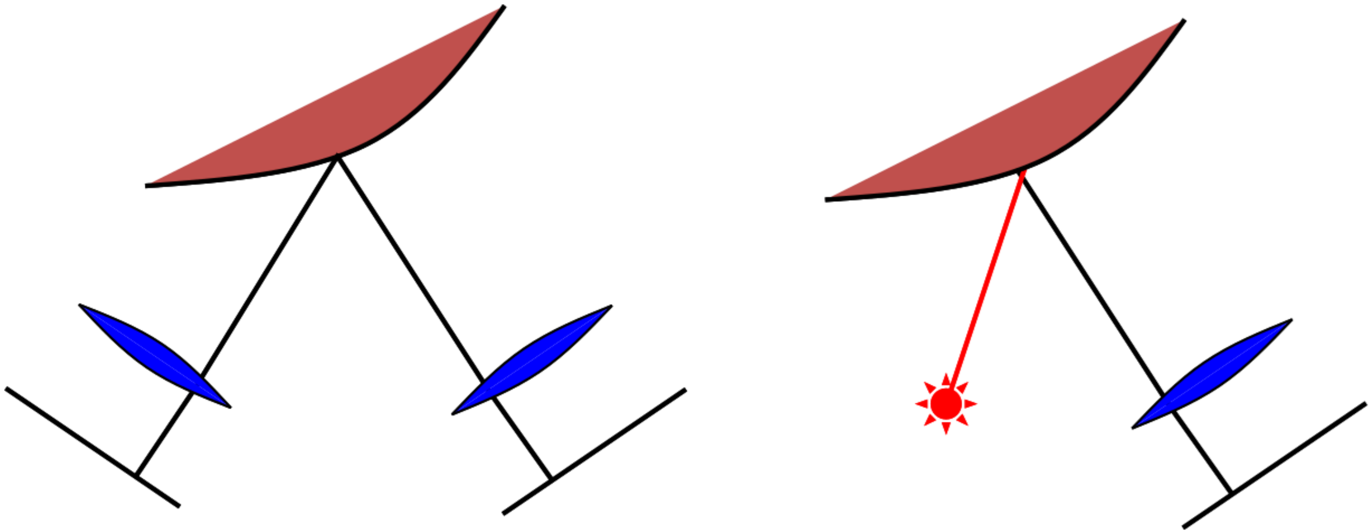
- In structured light correspondence is more constrained.
- We add information by using either a single stripe of light or a relatively unique light pattern.
- **Either** match across a single laser stripe.
- **Or,** instead of matching one pixel at a time, we can exploit the knowledge about the light pattern and try to match a set of points at a time.



Correspondence becomes easier!

Passive *vs.* Active Acquisition

Both passive and active methods follow the same underlying principle of ray triangulation.



Passive Setup **Active Setup**

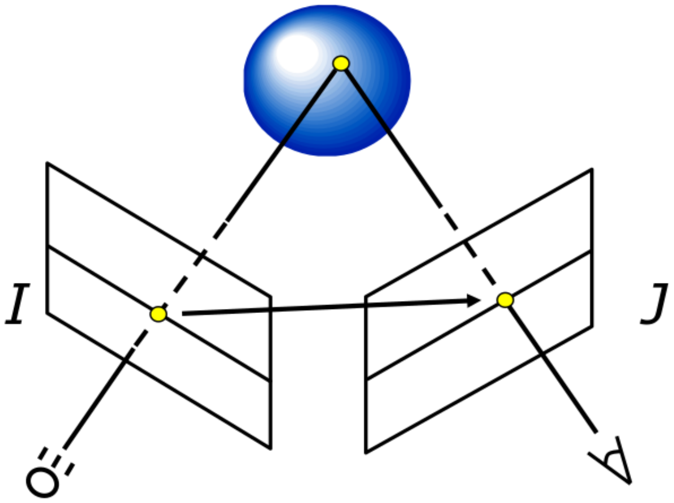
Active Acquisition

- Very simple approach:
  Given a projector I and a camera J with known relative position

- For each pixel of projector I
  - turn pixel on
  - find bright dot in camera image J
  - intersect rays → 3D point

- ***Slow,*** because we iterate over all pixels
- But finding correspondences is simple

- Better approaches?



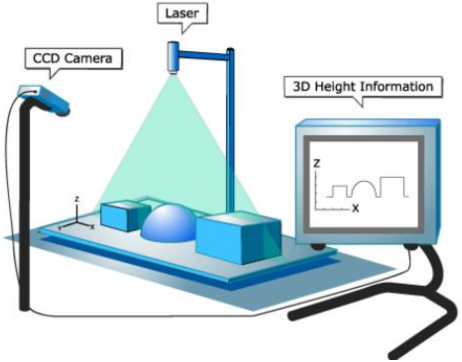
- How to make it faster?

Structured Light: Basic Concept

- The triangulation idea can be applied in a setup that uses a projector (or laser beam) and a camera, instead of 2 cameras. The ray of the controlled incident light replaces the projection ray of the 2nd camera.
- Object surfaces are illuminated with a known pattern of light
- The structured light is the main source of illumination
- Depending on the shape of the object the pattern is distorted.
- A camera captures the distorted pattern.

Prior Knowledge

- known geometry of light pattern
- known relative position of light and camera.



Structured Light: Basic Concept

- Th ... at uses a projector (or laser
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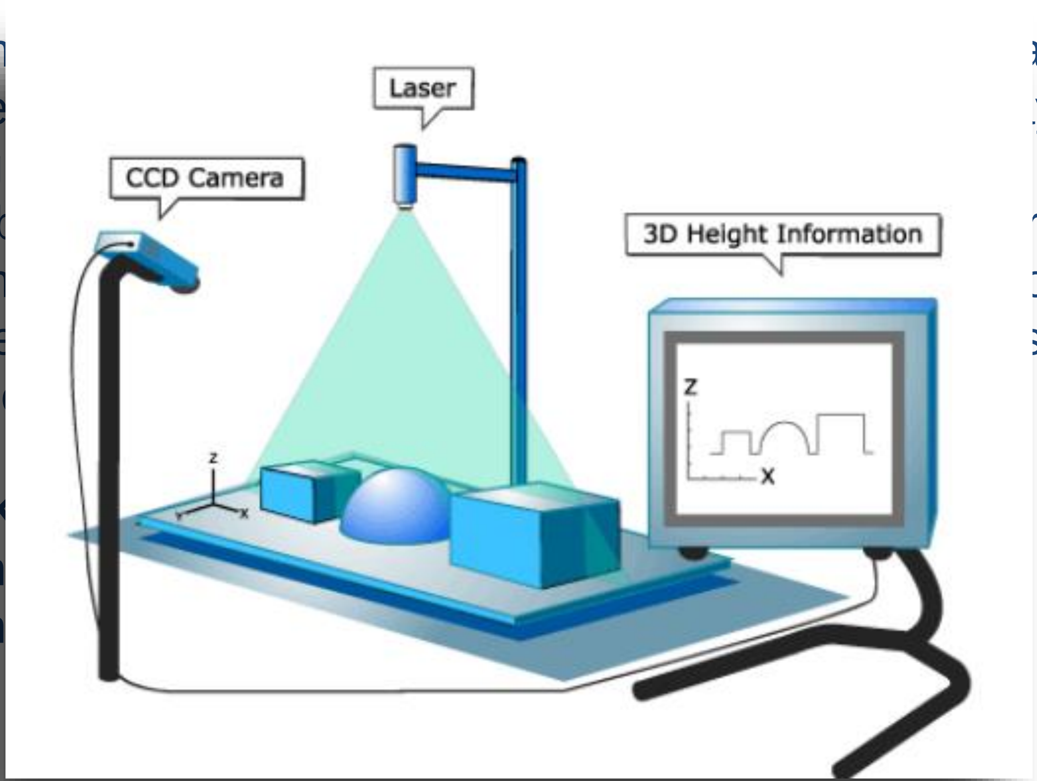

Prior K

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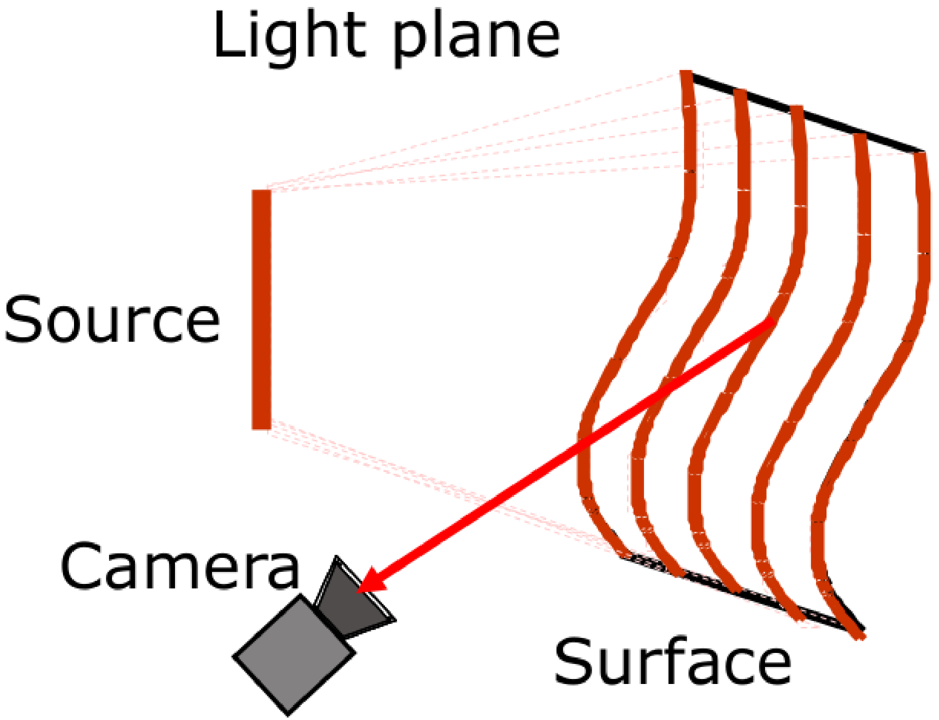
Single Stripe Scanning

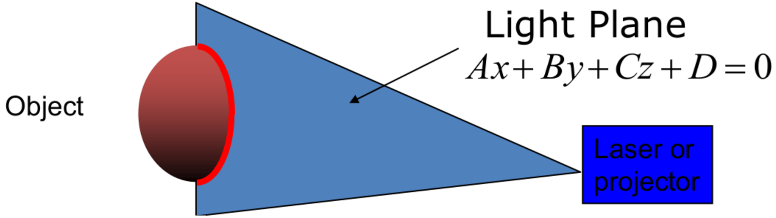
Optical triangulation

- Project a single stripe of light (from laser or projector)
- Scan it across the surface of the object
- This is a very precise version of structured light scanning
- Good for high resolution 3D, but needs many images and
- takes time



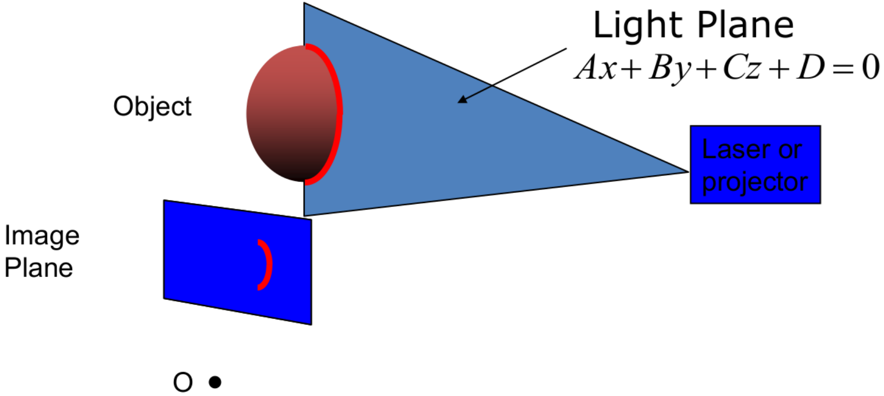
Triangulation with Light Plane

- Project a single stripe of light onto an object



Triangulation with Light Plane

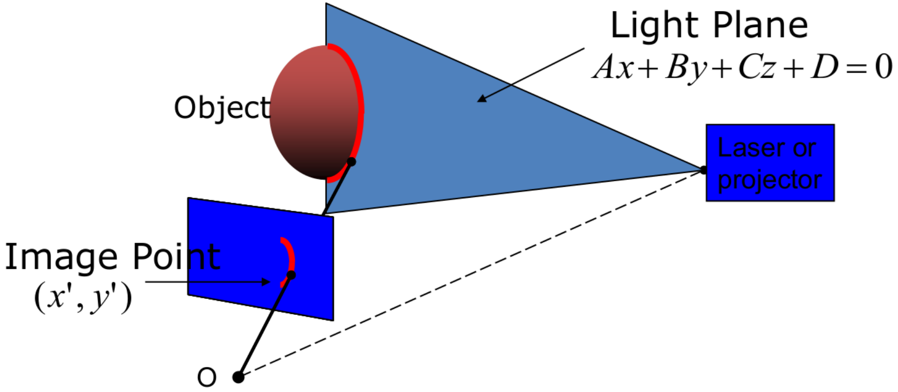
- Project a single stripe of light onto an object
- Capture the scene with a camera with COP O.
- The camera is at an angle with the light source.



Triangulation with Light Plane

Depth from ray-plane triangulation:

> Intersect camera ray with light plane



$$x = x'z/f \qquad z = \frac{-Df}{Ax' + By' + Cf}$$

$$y = y'z/f$$

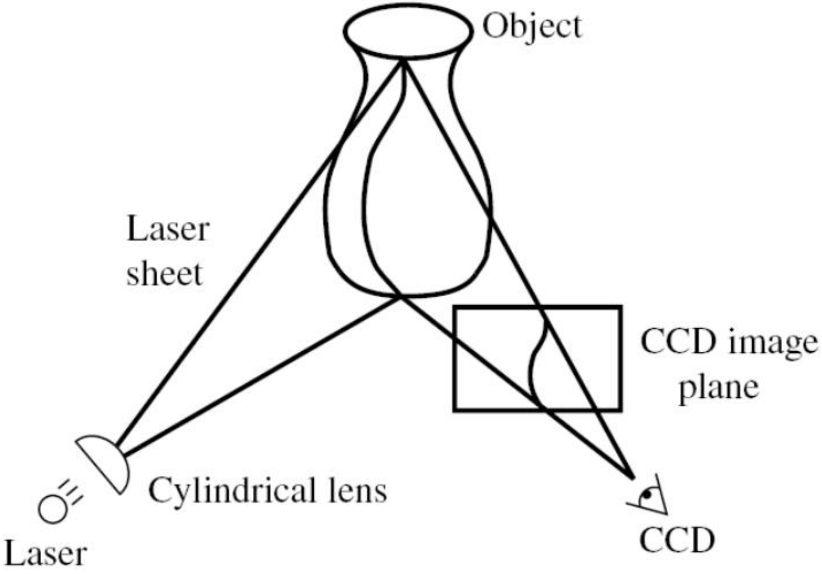
Triangulation with Light Plane

- now we only have to iterate over planes
  - much less than over all pixels
  - much faster
- does not require a real projector
- a simple laser shield that can sweep through the scene is sufficient
- ...or the object is moved through a fixed laser shield

Example: Laser Scanner

+ very accurate < 0.01 mm

− still more than 10 sec per scan

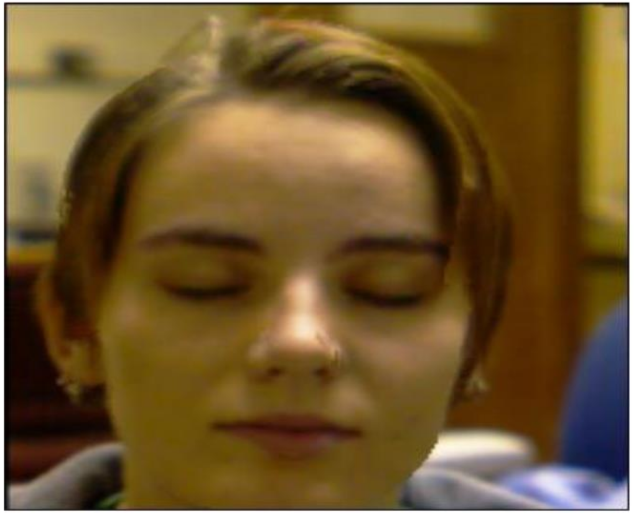


Cyberware® face and head scanner

Heinrich Bülthoff

Example: Portable Laser Scanner

Minolta VIVID 910
3D Laser Scanner



- How to make it faster?

Faster Acquisition?

- Project multiple stripes simultaneously
- Correspondence problem: which stripe is which?
- Common types of patterns:
  - Binary coded light striping
  - Gray/color coded light striping

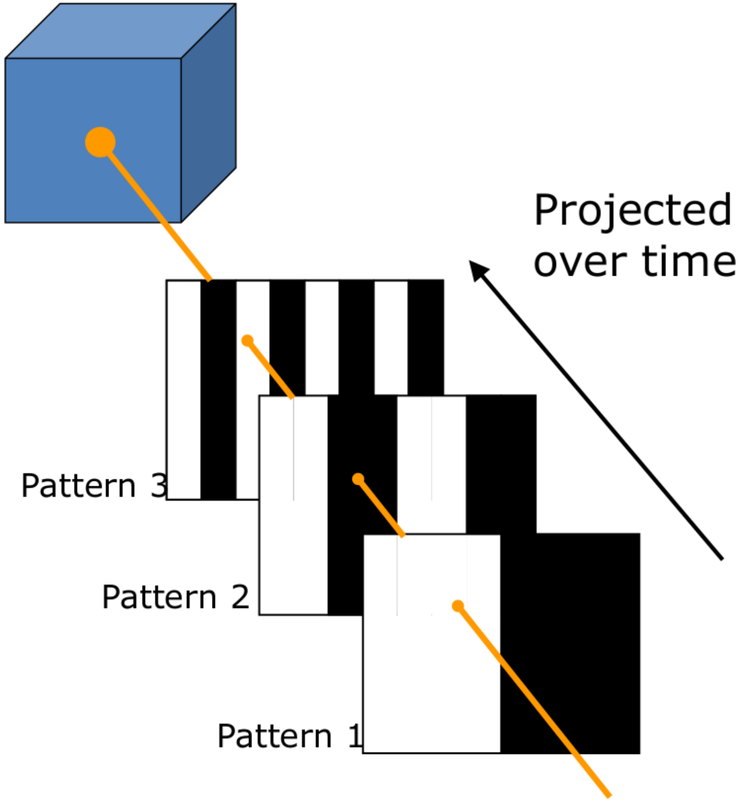
Binary Coding Idea

Faster:

$(2^n - 1)$ stripes in n images.

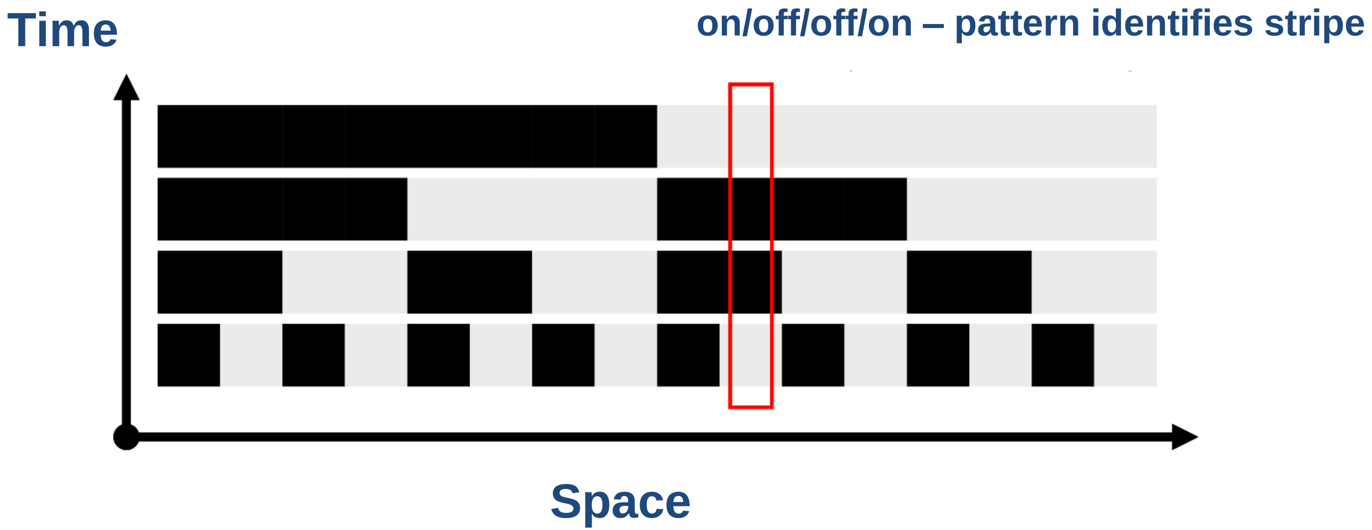
Example:

3 binary-encoded patterns which allows the measuring surface to be divided in 8 sub-regions

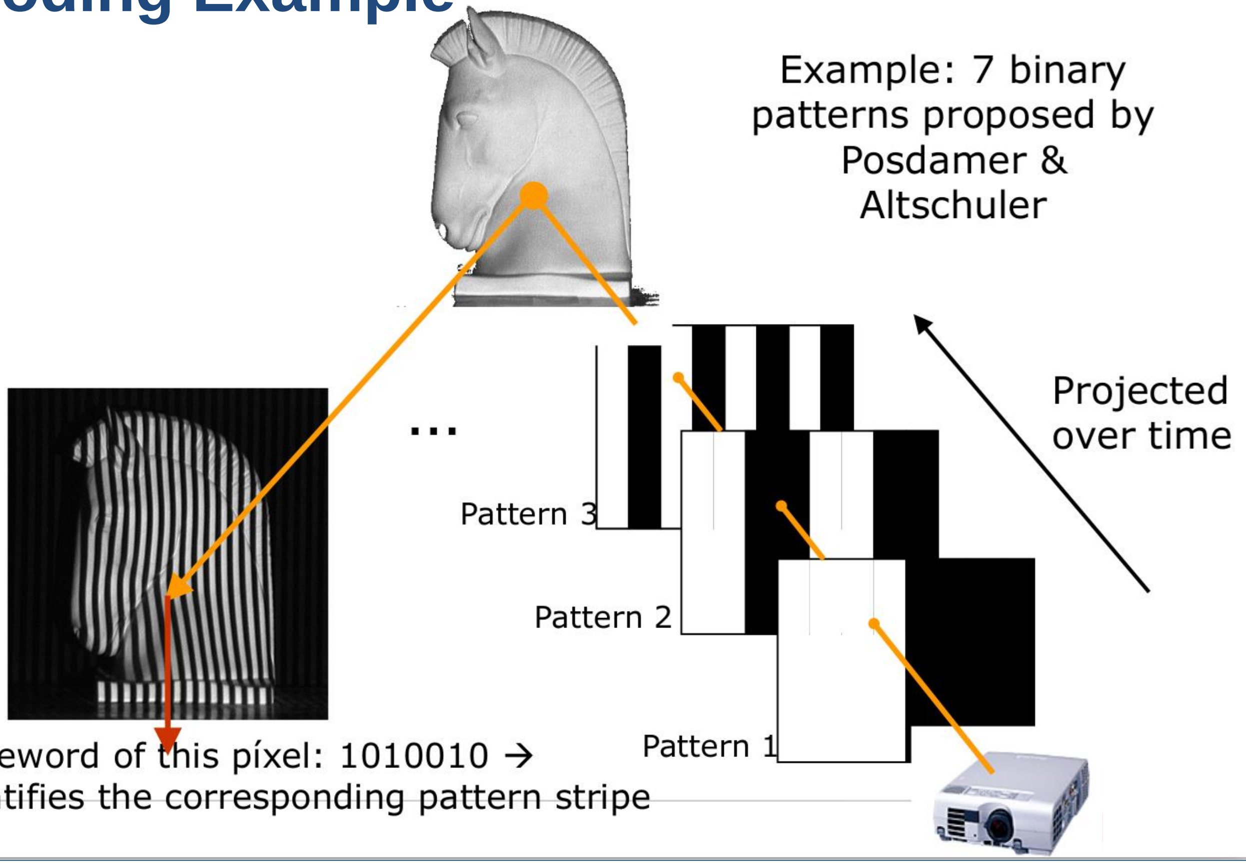


Uniqueness of Binary Coding

- Assign each stripe a unique illumination code over time [Posdamer 82].
- Each stripe has a unique on/off pattern over the frames.
- Thus, it is easy to identify the plane of illumination.

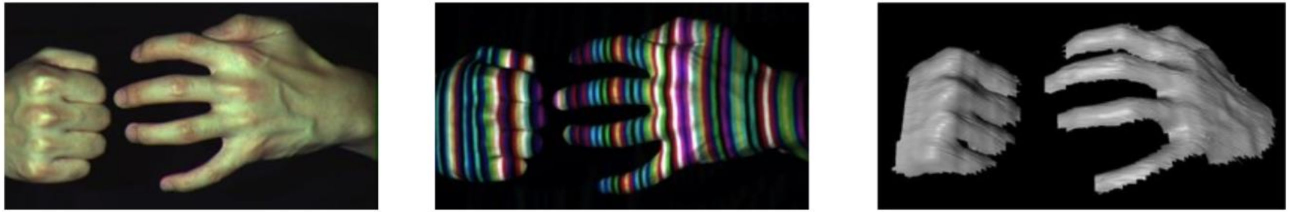


Binary Coding Example

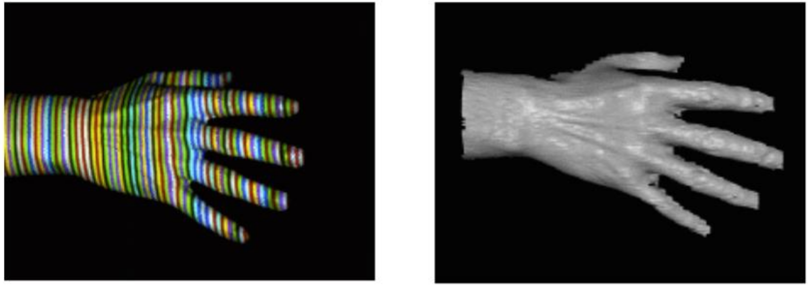


Codeword of this píxel: 1010010 → identifies the corresponding pattern stripe

More Complex Light Patterns



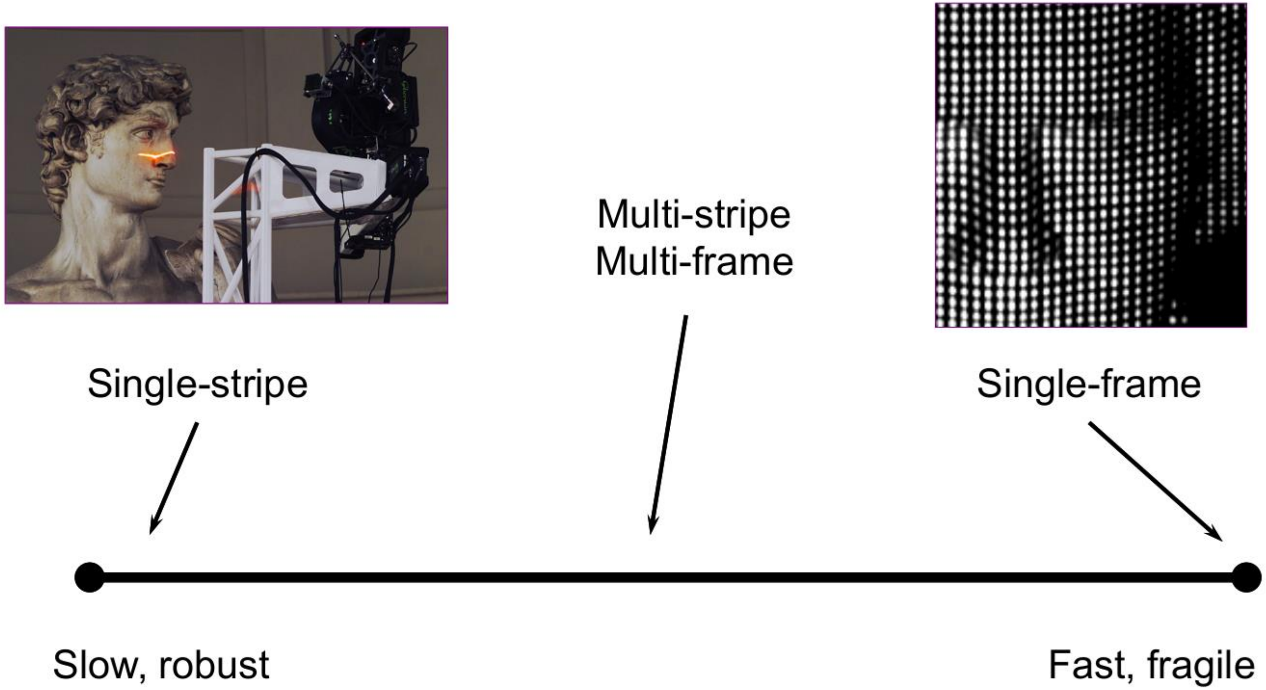
Works despite complex appearances



Works in real-time and on dynamic scenes

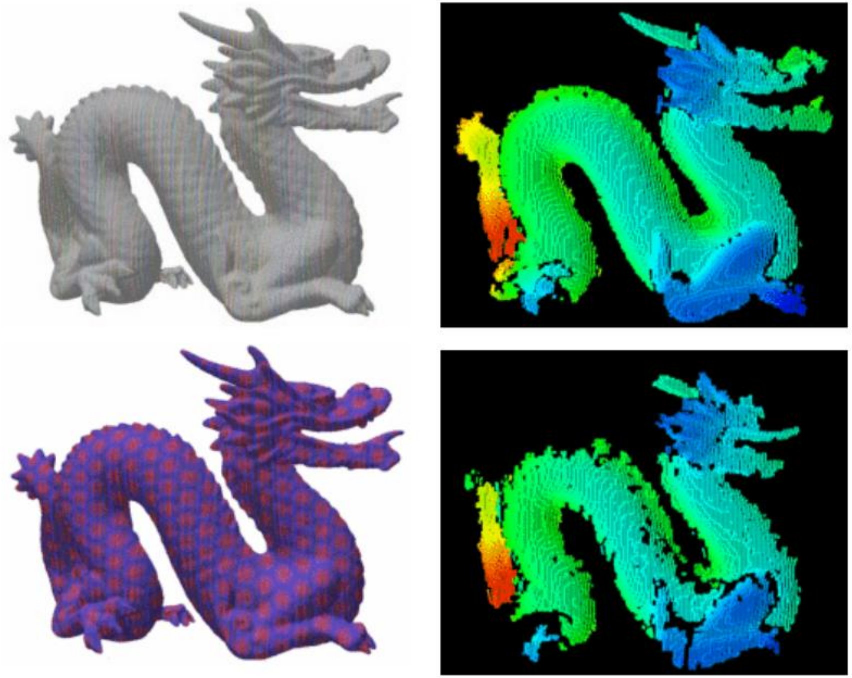
- Need very few images (one or two).
- But needs a more complex correspondence algorithm

Continuum of Triangulation Methods



Structured Light and Texture

- Structured Light works when there are no other light sources and the object has uniform color
- Other illumination and texture can disturb measurement



How to capture appearance?

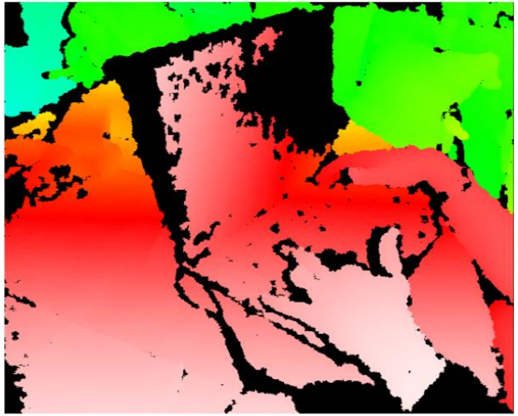
Kinect Sensor (and many successors)

- Kinect is marketed as a motion sensing device.

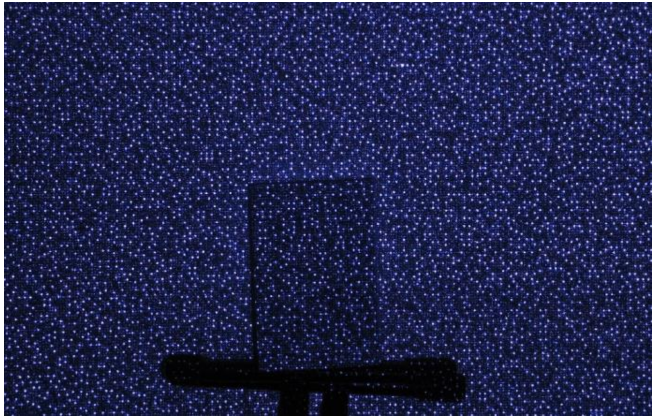
- It has a number of sensors:
  - An RGB camera (the middle of the 3 lenses)
  - A unique structured-light system (projector is on the left and gray-scale camera is on the right)
  - 4 microphones distributed along its length, to better locate (via triangulation) the sources of voices.

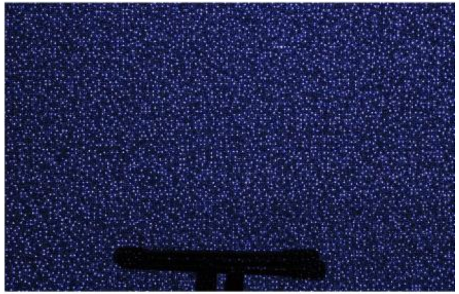
Kinect "Range Camera"

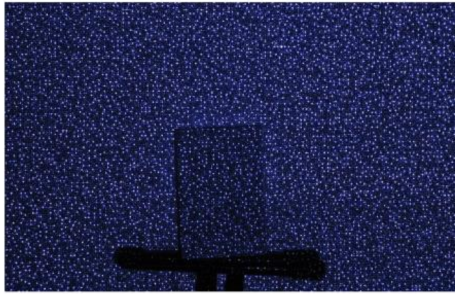
- The projector projects an imperceptible infrared light pattern.
- Adjustable depth sensing range between 1.2 and 3.5m.
- The patent is on the "special laser point pattern".
- It generates a speckle pattern that varies along the Z direction.
- It is created by positioning a holographic diffuser in-front of a near IR laser. The diffuser causes the speckle pattern.

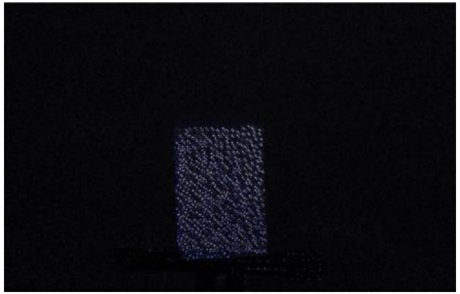


Kinect “Range Camera” - continued









- Depth is computed by measuring the relative shift of the features of the random pattern in the image relative to the pattern in a known reference image.
- The shift (much like the binocular stereo shift) is identified by using window-based normalized cross-correlation.

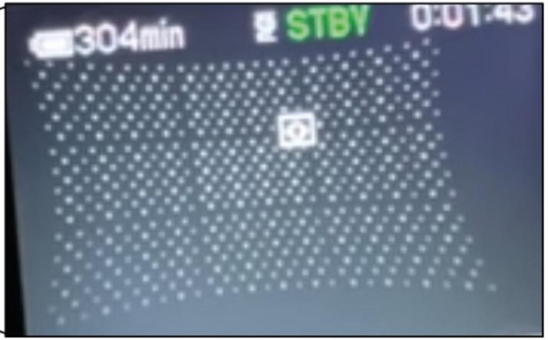
ToF: A completely different system

- ToF: Time of Flight
  - A short light pulse is emitted, each pixel measures the time, until the light arrives
  - distance can be determined from this time
  - extremely short times (speed of light)
- Used in Kinect One

Apple iPad Pro LiDAR module - Principle

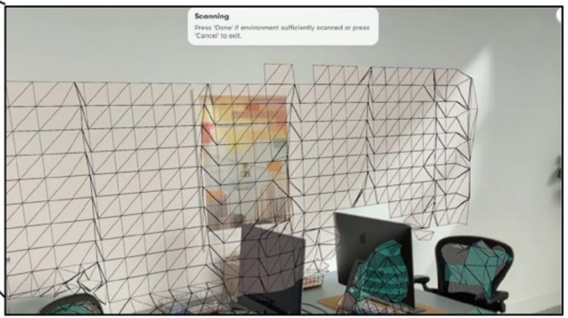
(Source: Apple IpAD Pro LiDAR Module structural, process & cost report, System Plus Consulting, 2020)

The VCSEL and the DOE project a dot matrix of 9 x 64 dots.



MobileReviewsEh – Courtesy of YouTube, 2020

The SPAD NIR CIS sensor measures the distance between the iPad and the 9x64 dots and the processor creates the map of the environment.

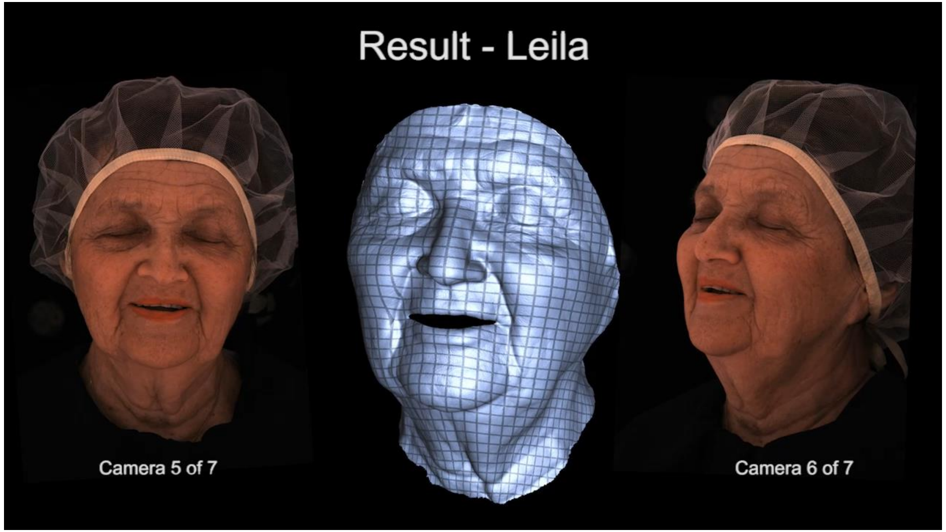


Courtesy of Apple, 2020

- https://www.youtube.com/watch?v=4GiLAOtjHNo

Open Challenges

- Remaining challenges:
  - Controlled lab conditions
  - Specular reflections
  - Expensive setups
  - Natural expressions vs. FACS
  - Ethical challenges: bias, privacy



Capture at Disney Research - Beeler et al. SIGGRAPH 2011

Image Sources

1. The commercial stereo sensor is the Bumblebee2 from “Point Grey” http://www.ptgrey.com/products/bumblebee2/images/BB2_white_background_large.jpg
1. The homemade stereo setup is courtesy of the “Grau goes Color” blog http://grauonline.de/wordpress/
2. The stereo eyeglasses are the “Vuzix Wrap 920AR Video Eyewear” as shwon in http://www.trendygadget.com/category/digital-cameras/
3. The stereo example is from H. Tao et al. “Global matching criterion and color segmentation based stereo”
4. The structured light example of the female-bust sculpture is courtesy of S. Yamazaki http://www.dh.aist.go.jp/~shun/research/dlp/fig/structured.jpg
5. The example of the recovered unfinished face sculpture is from “The Digital Michelangelo Project” http://www.graphics.stanford.edu/projects/mich/
6. The picture of the scanner used in the Michelangelo project is courtesy of Cyberware http://www.cyberware.com/products/scanners/lss.html
7. The “Head and Face Scanner” is by Cyberware http://www.cyberware.com/guides/cyscan/info/pxPlatform.html
8. The figure that shows the basic concept behind structured light is courtesy of “Stocker Yale” http://www.stockeryale.com/i/lasers/structured_light.htm
9. The example of the black and white structured light pattern projected on the sun sculpture is from Google’s code on structured light http://code.google.com/p/structured-light/updates/list
10. A number of slides in this presentation have been adapted by the presentation of S. Narasimhan, http://ww.cs.cmu.edu/afs/cs/academic/class/15385-s06/lectures/ppts/lec-17.ppt
11. The Kinect Speckle Field information is from “Kinect Hacking 101”, http://www.futurepicture.org/?p=97 , “Kinect Hacking 103”, http://www.futurepicture.org/?p=116

- **Finish early ☺**
  - Time for you to fill out the evaluation form…