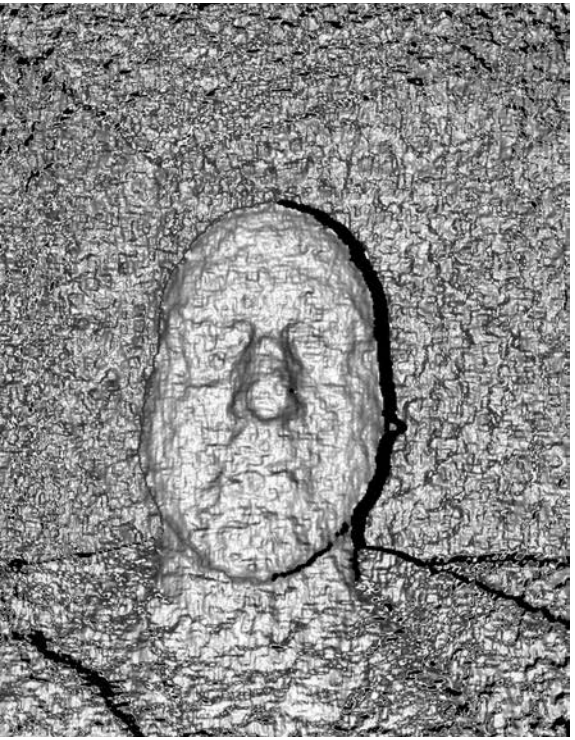
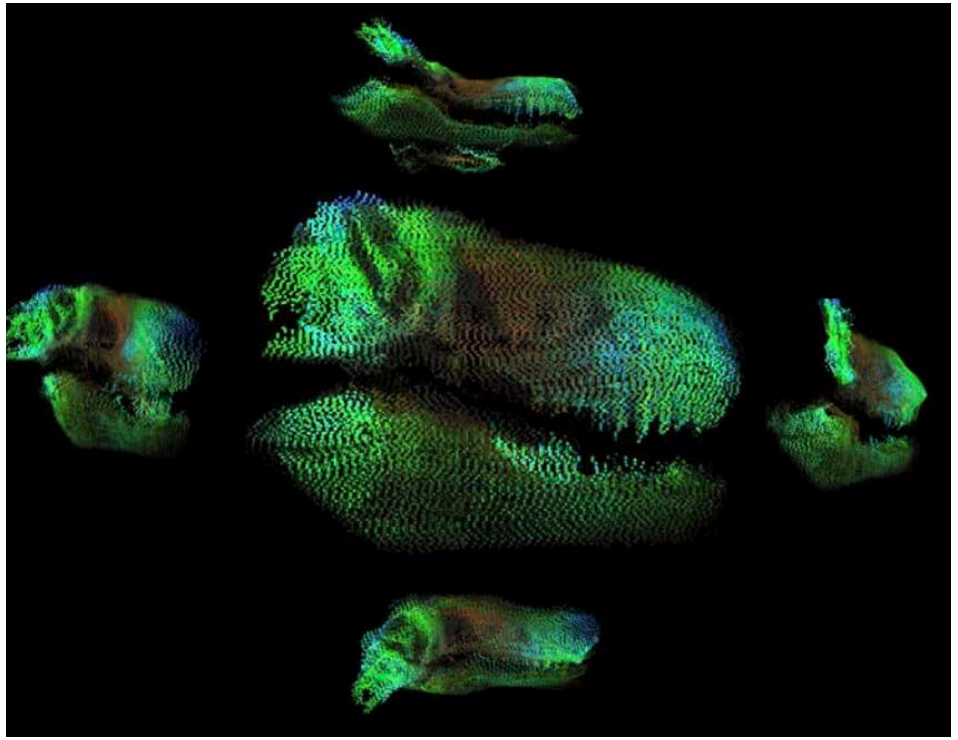
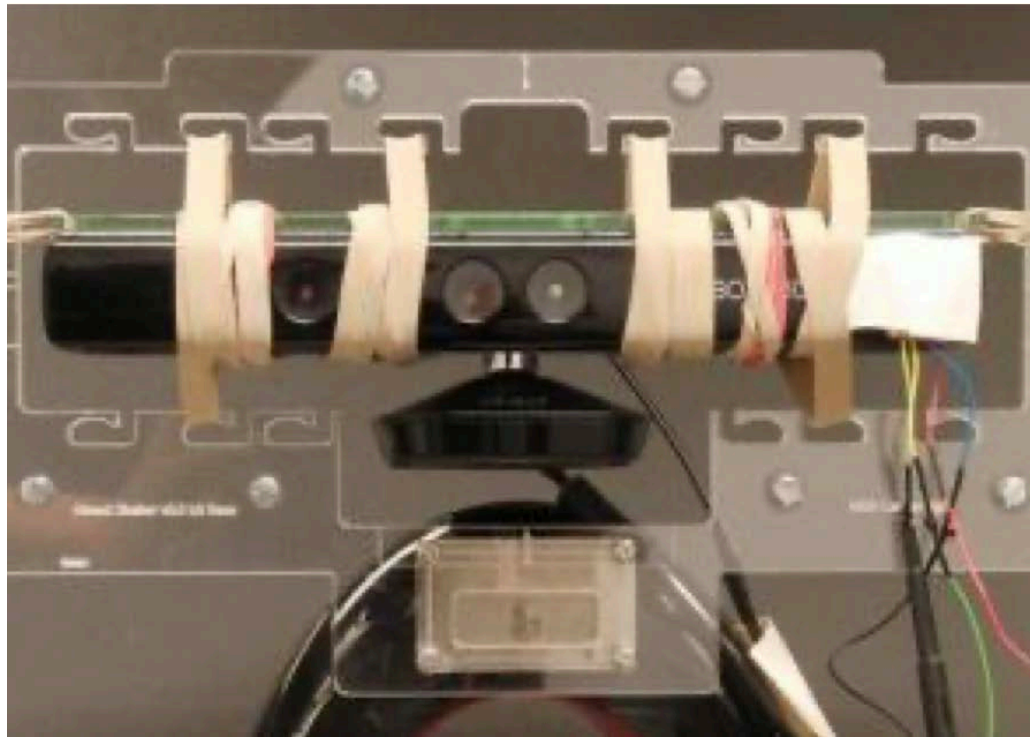
Visual Computing I:

Interactive Computer Graphics and Vision







Practical Depth Sensing and Working with Range Data

Stefanie Zollmann and Tobias Langlotz

Last time..

The Fundamental Matrix

Notes:

$$p_1 = K_1[I\,|\,0]x$$
$$p_2 = K_2[R\,|\,t]x$$

- One way to express $\mathbf{F}$ is

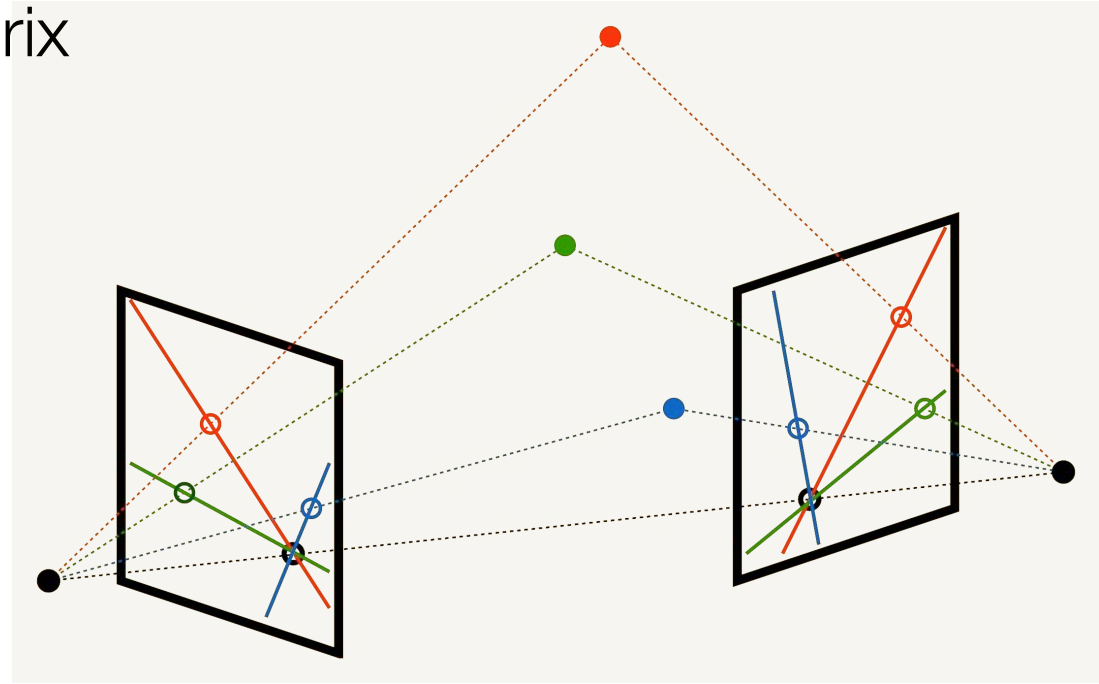
$$\mathbf{F} = \mathbf{K}_2^{-T}[\mathbf{t}]_\times \mathbf{R}\mathbf{K}_1^{-1}$$

- Here
  - $\mathbf{K}_1$ and $\mathbf{K}_2$ are the calibration matrices of the two cameras
  - $\mathbf{R}$ and $\mathbf{t}$ are the rotation and translation between them
  - $[\mathbf{t}]_\times$ is the matrix form of the cross product with $\mathbf{t}$:

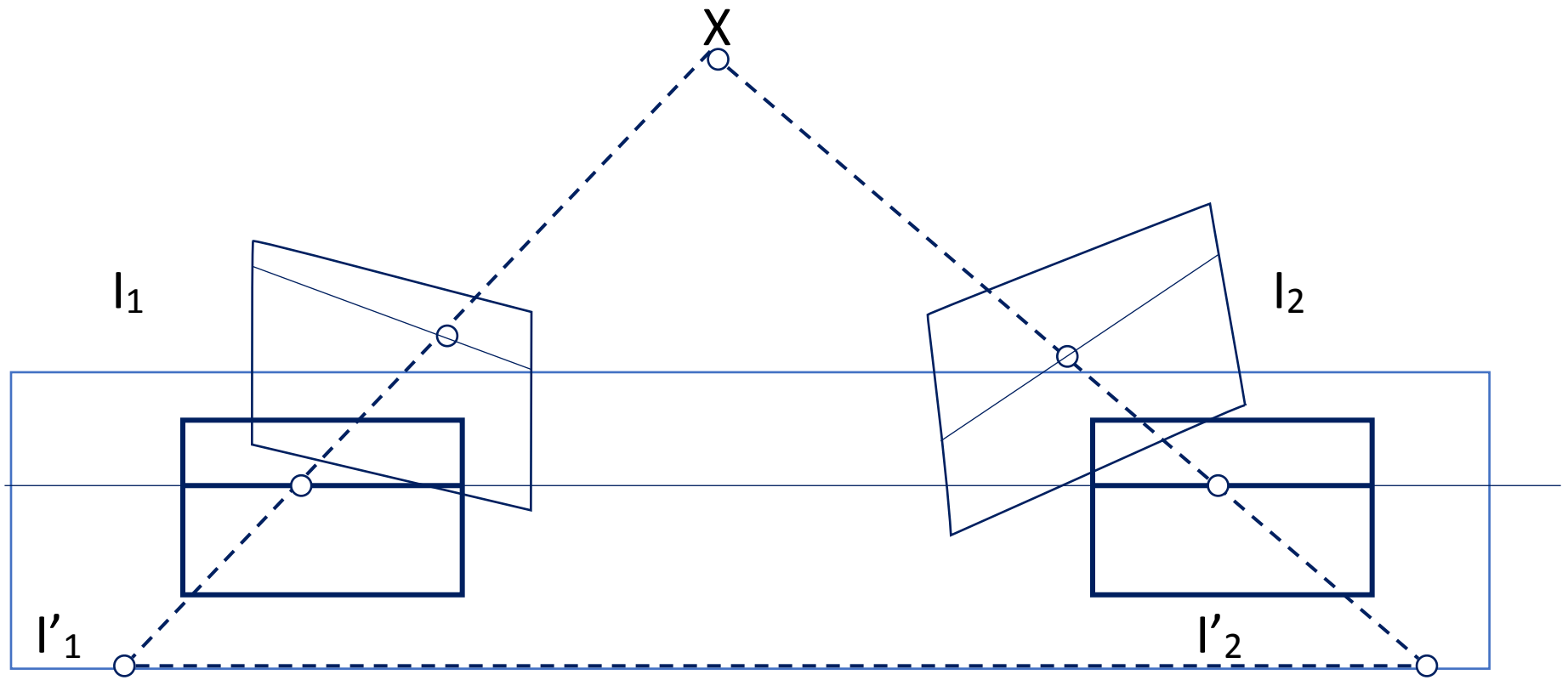
$$[t]_\times = \begin{bmatrix} 0 & -t_z & t_y \\ t_z & 0 & -t_x \\ -t_y & t_x & 0 \end{bmatrix}$$

The Essential Matrix

- For calibrated cameras
  - We can factor out $\mathbf{K}_1$ and $\mathbf{K}_2$ in $\mathbf{F} = \mathbf{K}_2^{-T}[\mathbf{t}]_\times \mathbf{R}\mathbf{K}_1^{-1}$
    - This gives us the essential matrix
      $$\mathbf{E} = \mathbf{K}_2^T \mathbf{F} \mathbf{K}_1 = [\mathbf{t}]_\times \mathbf{R}$$
  - $\mathbf{E}$ has only five DoF:
    - 3 for 3D rotation
    - 3 for 3D translation
    - Less 1 for unknown scale



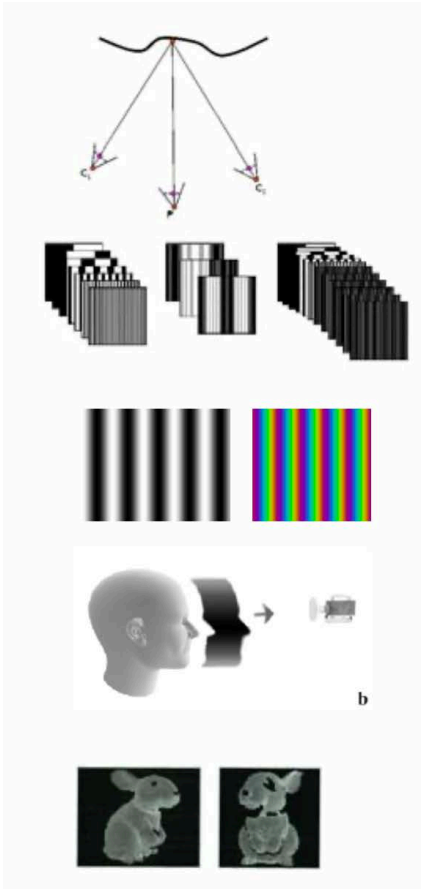
Stereo Rectification

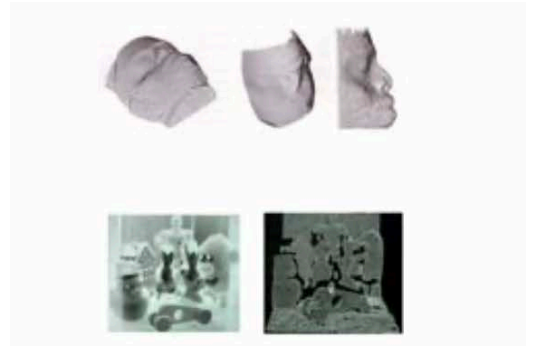


Today:
Practical Depth Sensing and Range Data

Overview

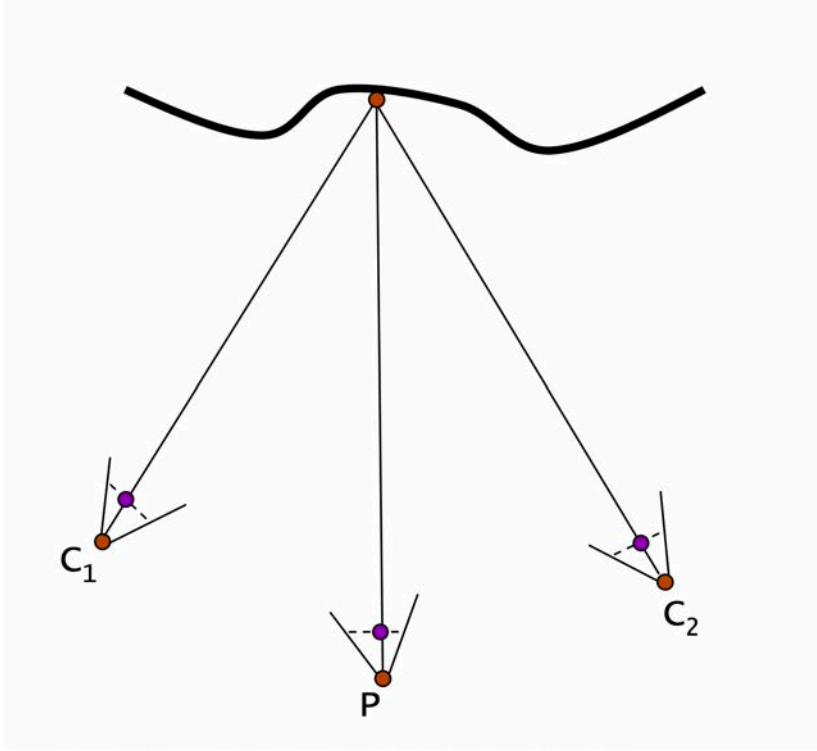
- Range Scanning
  - Passive:
    - Stereo or Multi-Camera
    - Active:
    - Structured Light Projection
    - Optical Time-of-Flight
      - Direct ToF
      - Indirect ToF
- Registration of Depth Maps
- Processing Depth Maps

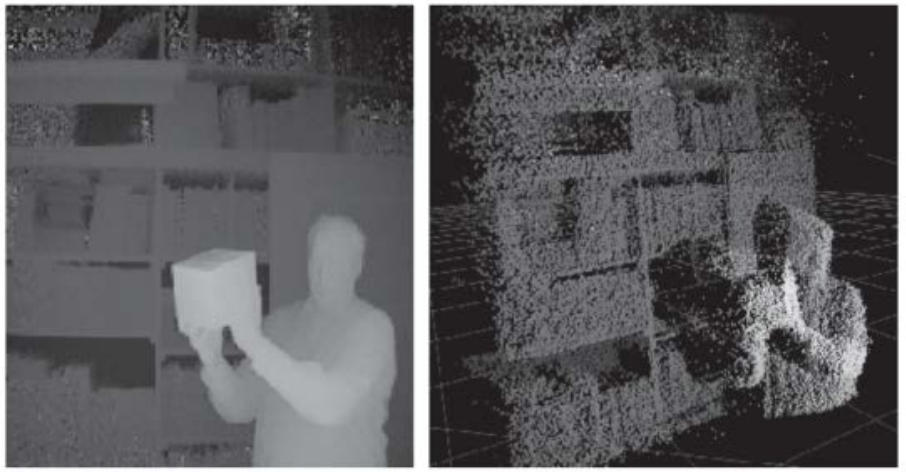




Range Scanning

- Range sensors:
  - Passive: >=2 cameras (stereovision)
  - Active: >=1 cameras + >=1 projectors (structured light)
- Result is depth information given as:
  - Range image / depth map store depth at pixel positions from a specific view (RGBD image)
  - A point cloud is a 3D dataset of discrete (X,Y,Z) surface points



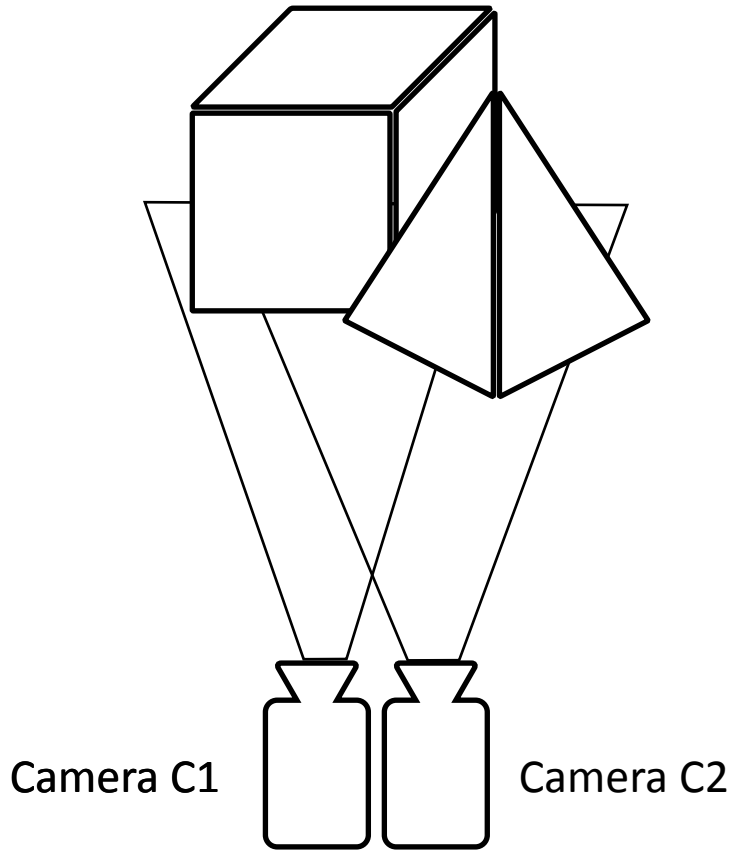


Depth Map Point cloud

Passive Range Scanning

Passive Range Scanning

- Two or more cameras
  - Stereo camera
  - Two cameras
  - One camera takes several photos from different perspectives
  - Multiple cameras
- Which one is the easiest and why?



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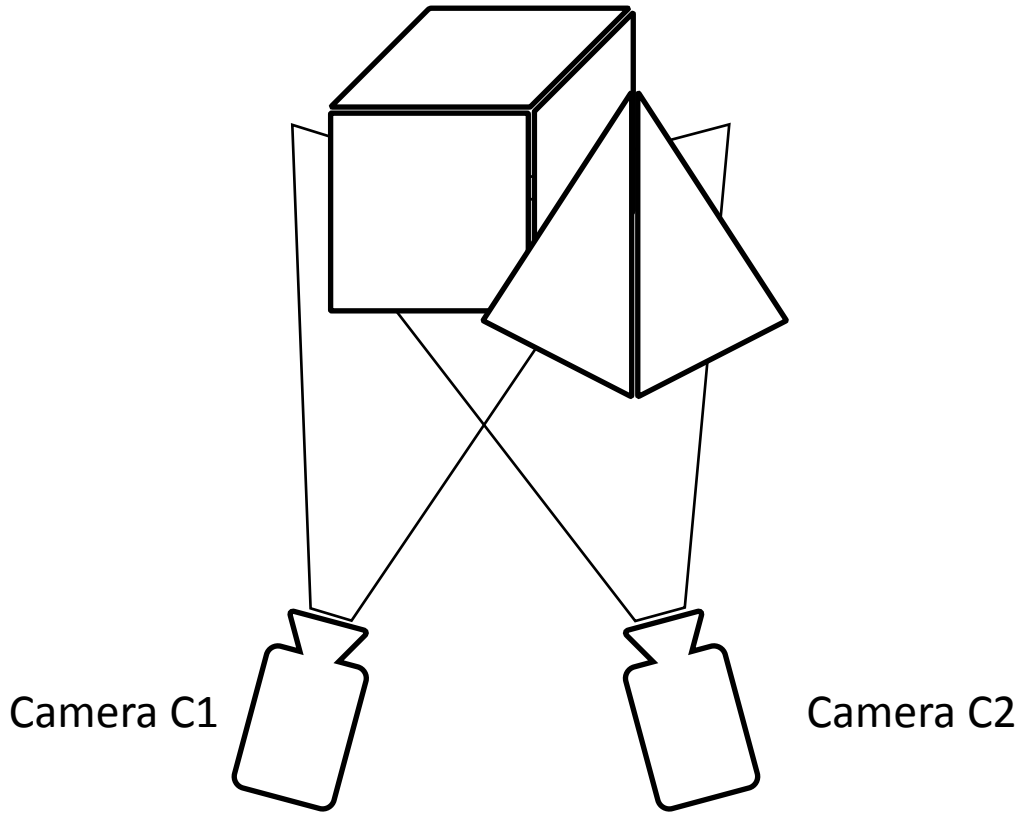

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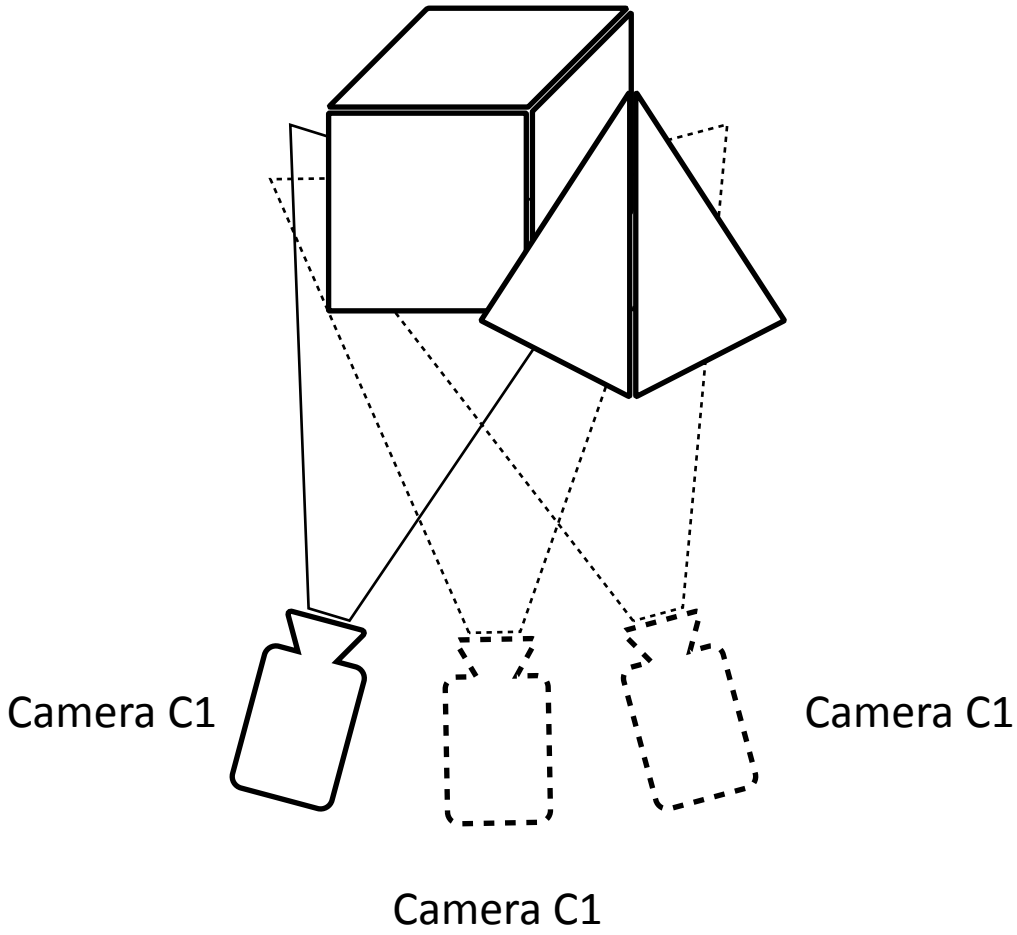

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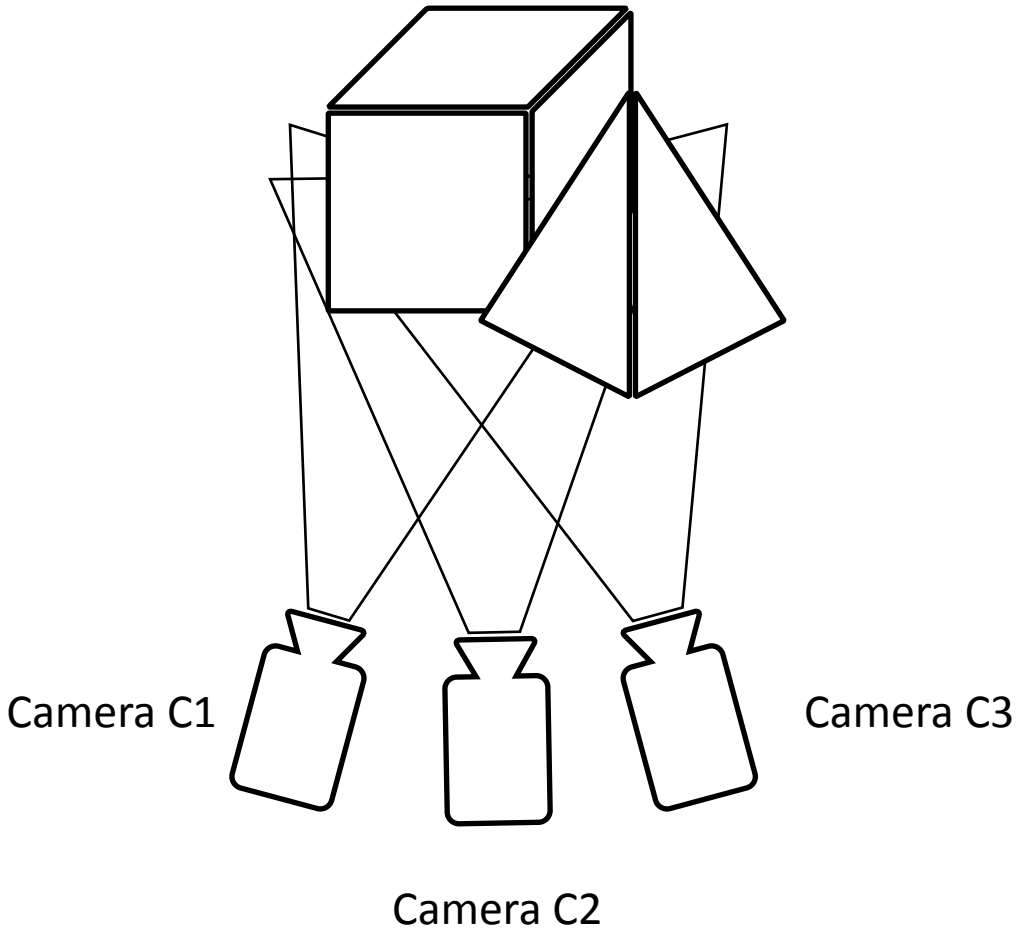

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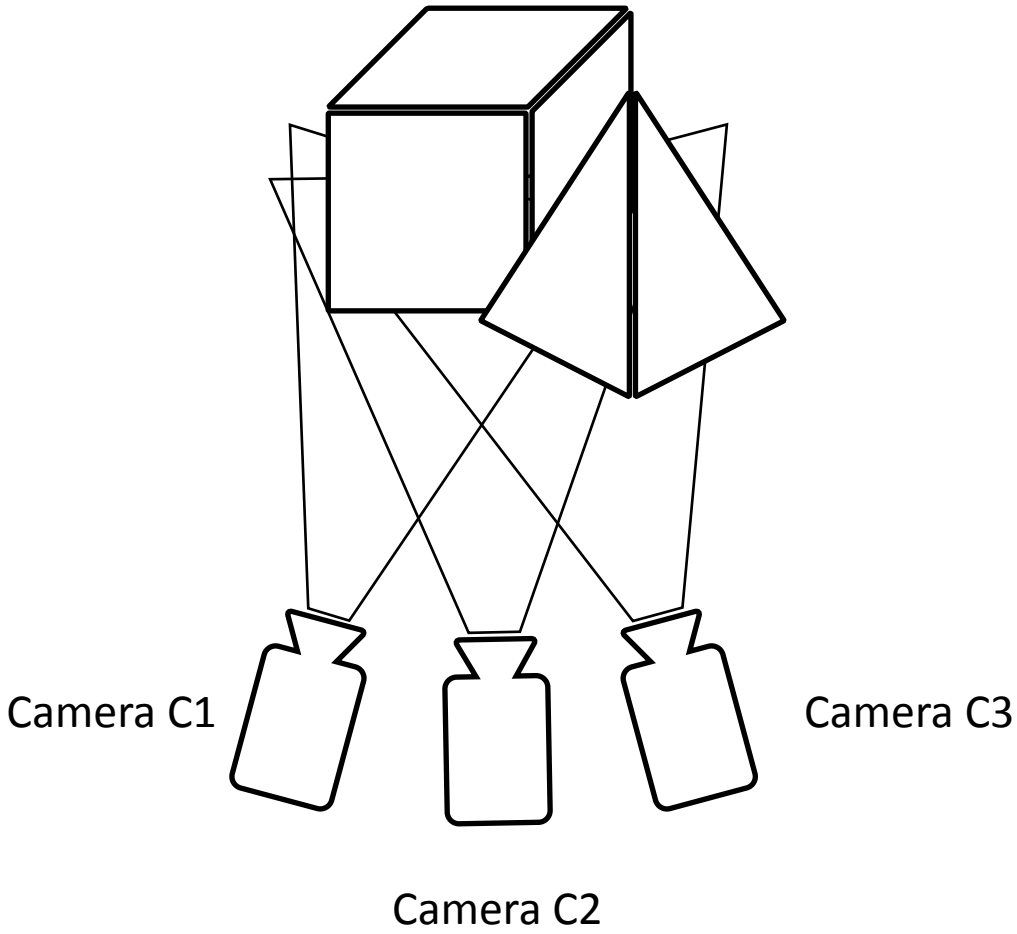

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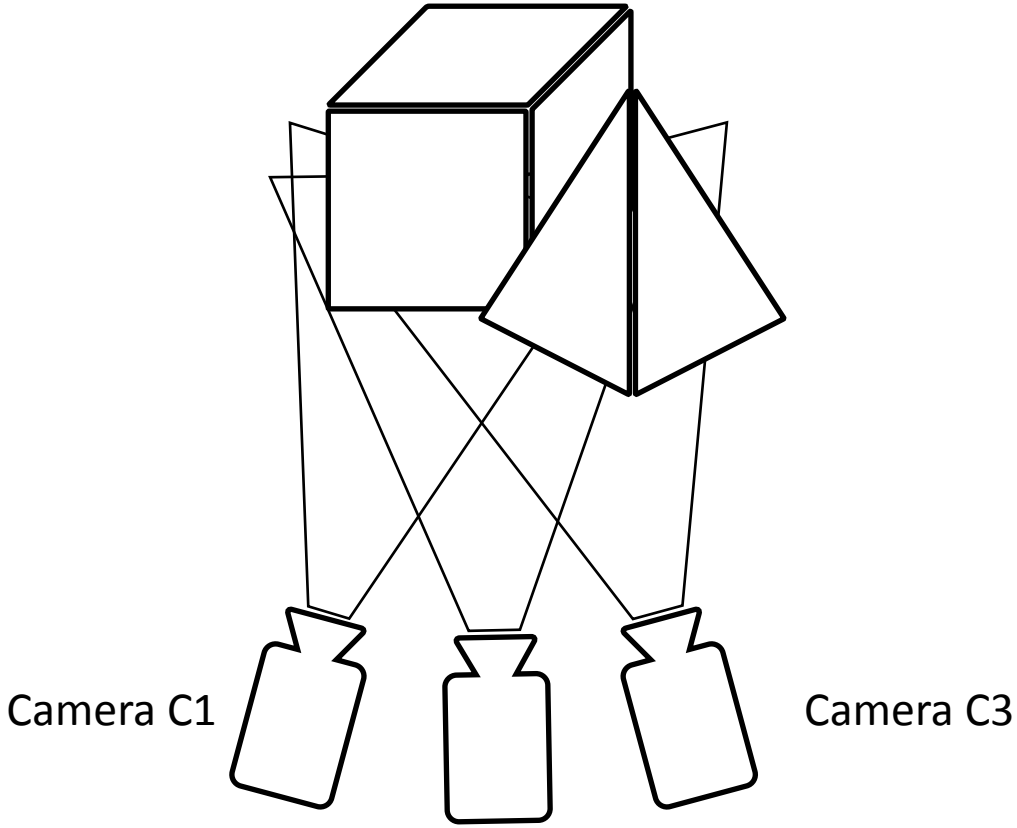
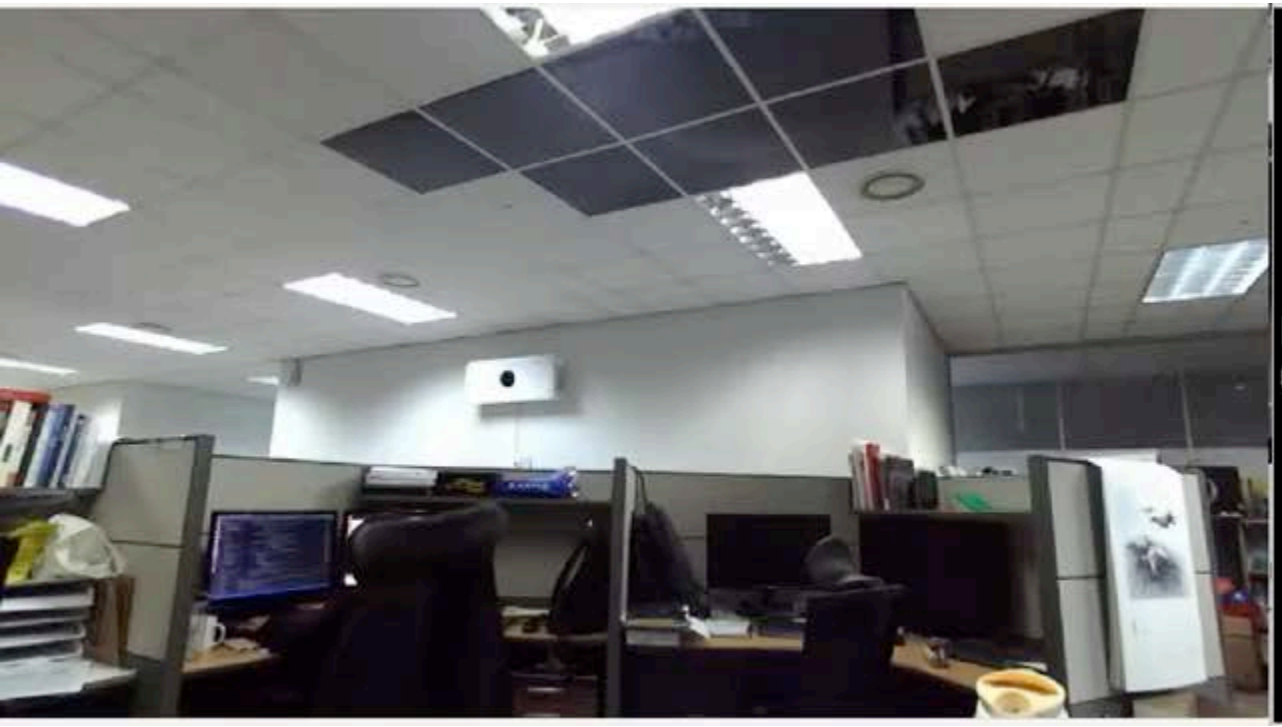
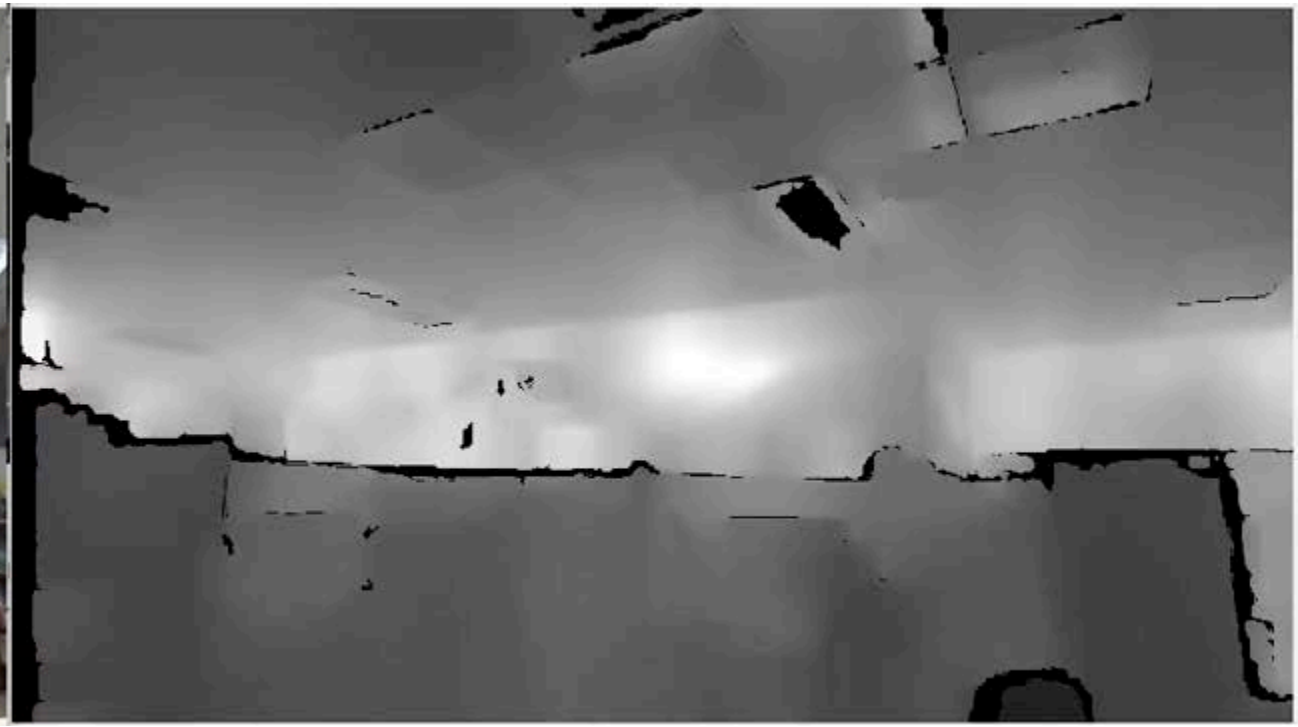


PointGrey Bumble Bee

Zed Mini

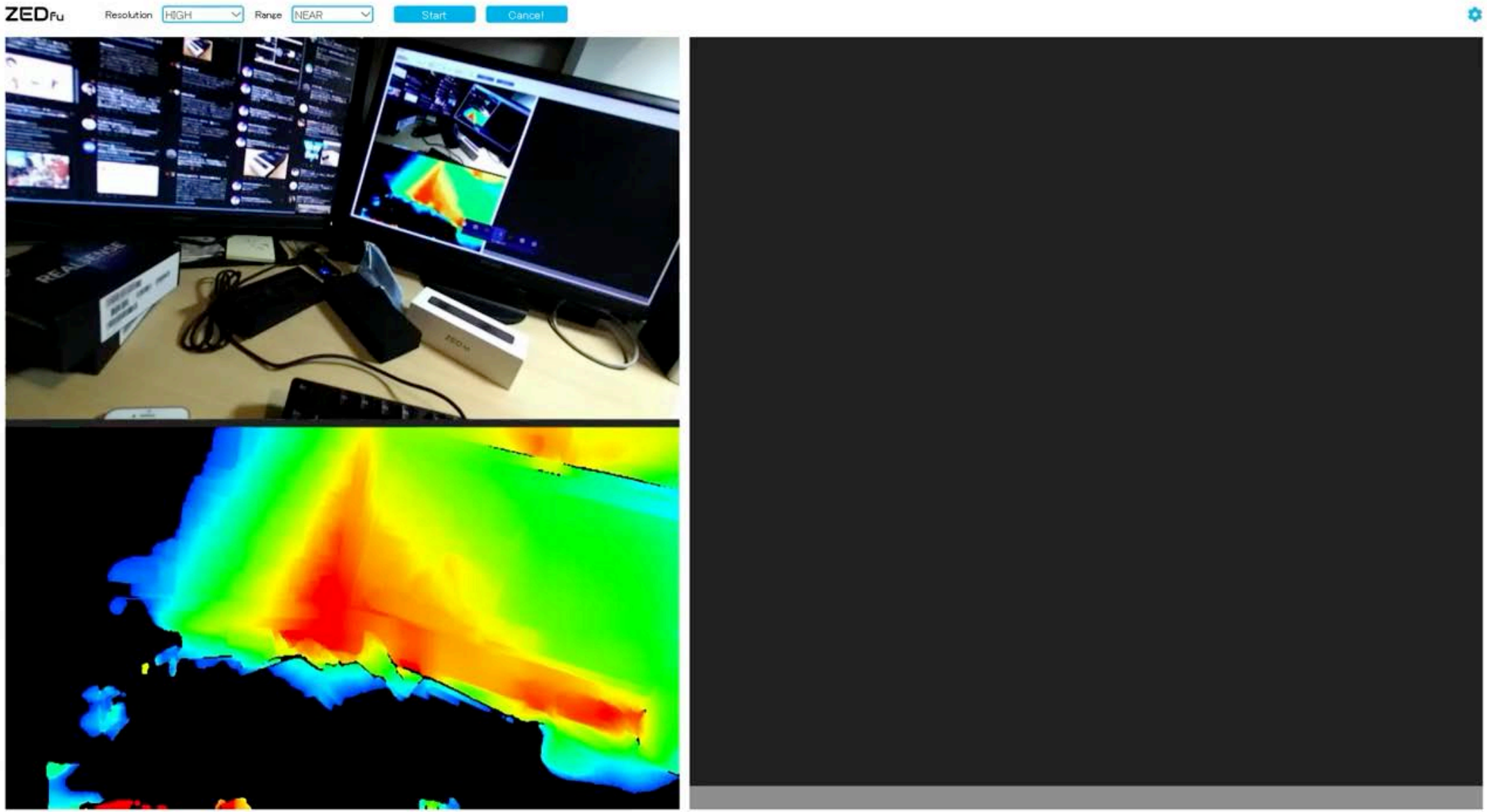
Passive range scanning





Youtube Taeyeon Kim

Passive range scanning

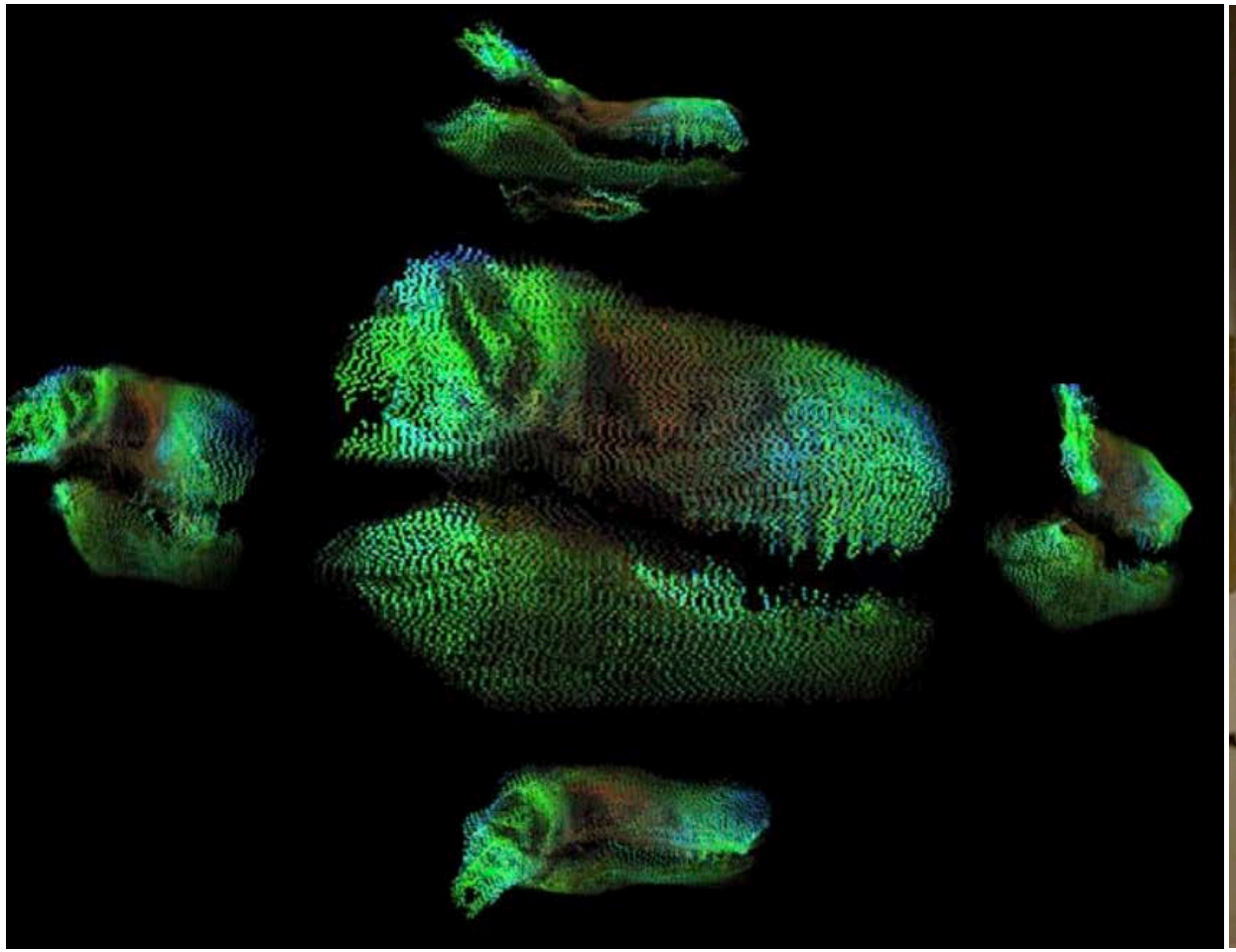


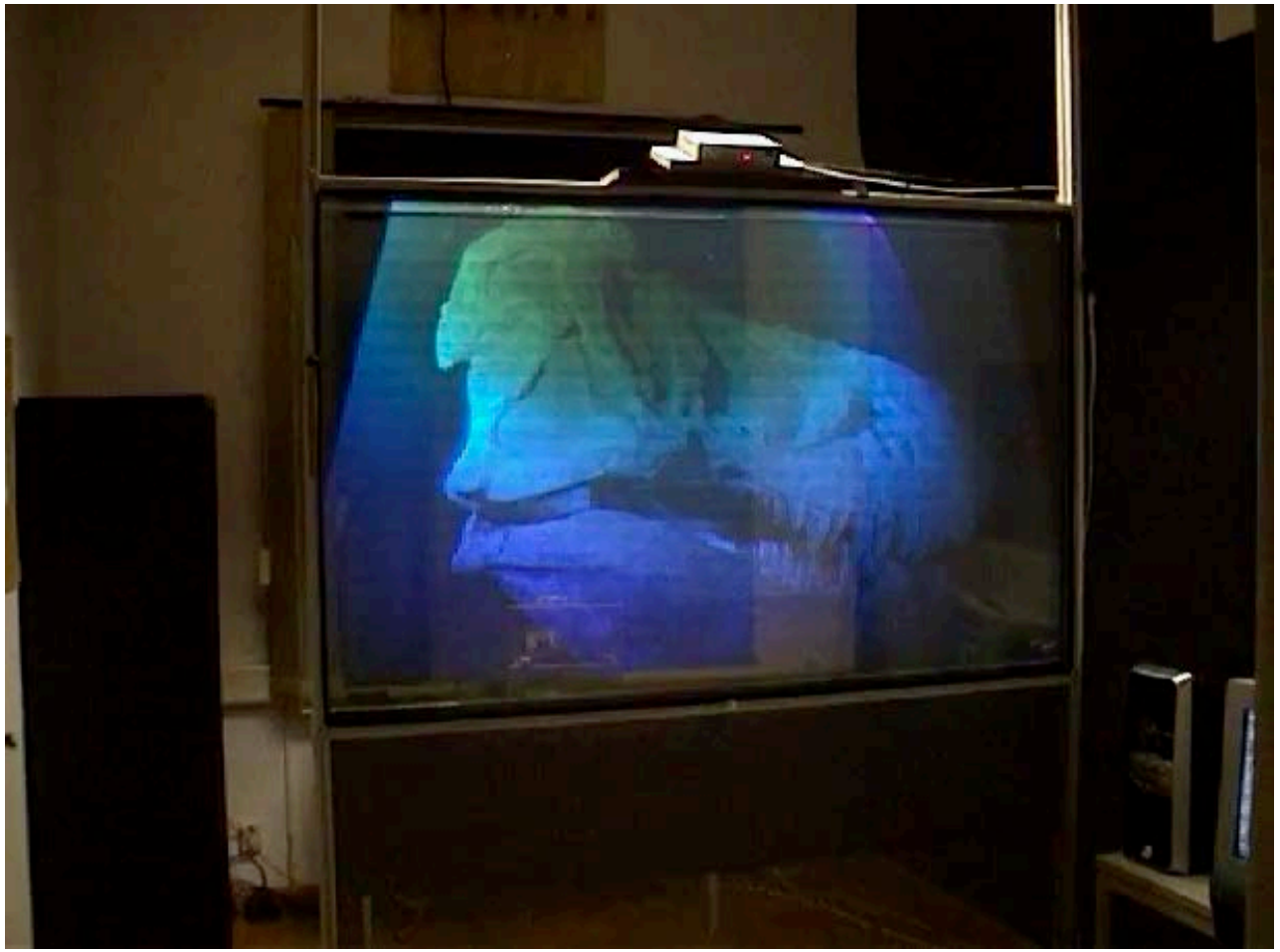
Youtube Atsizumi

Passive range scanning

Vexcel (YouTube Video: Skyline Software Systems)

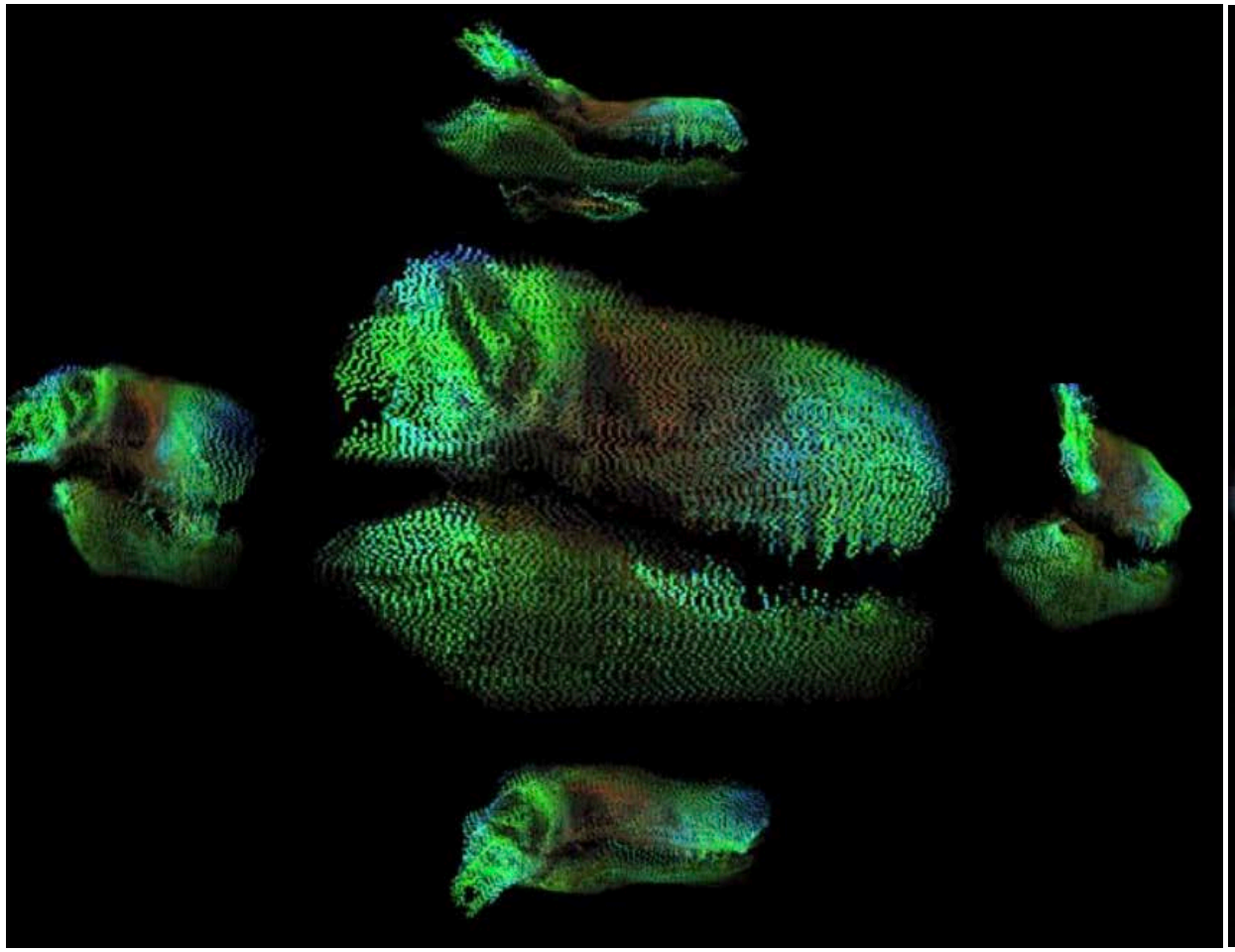
Passive range scanning

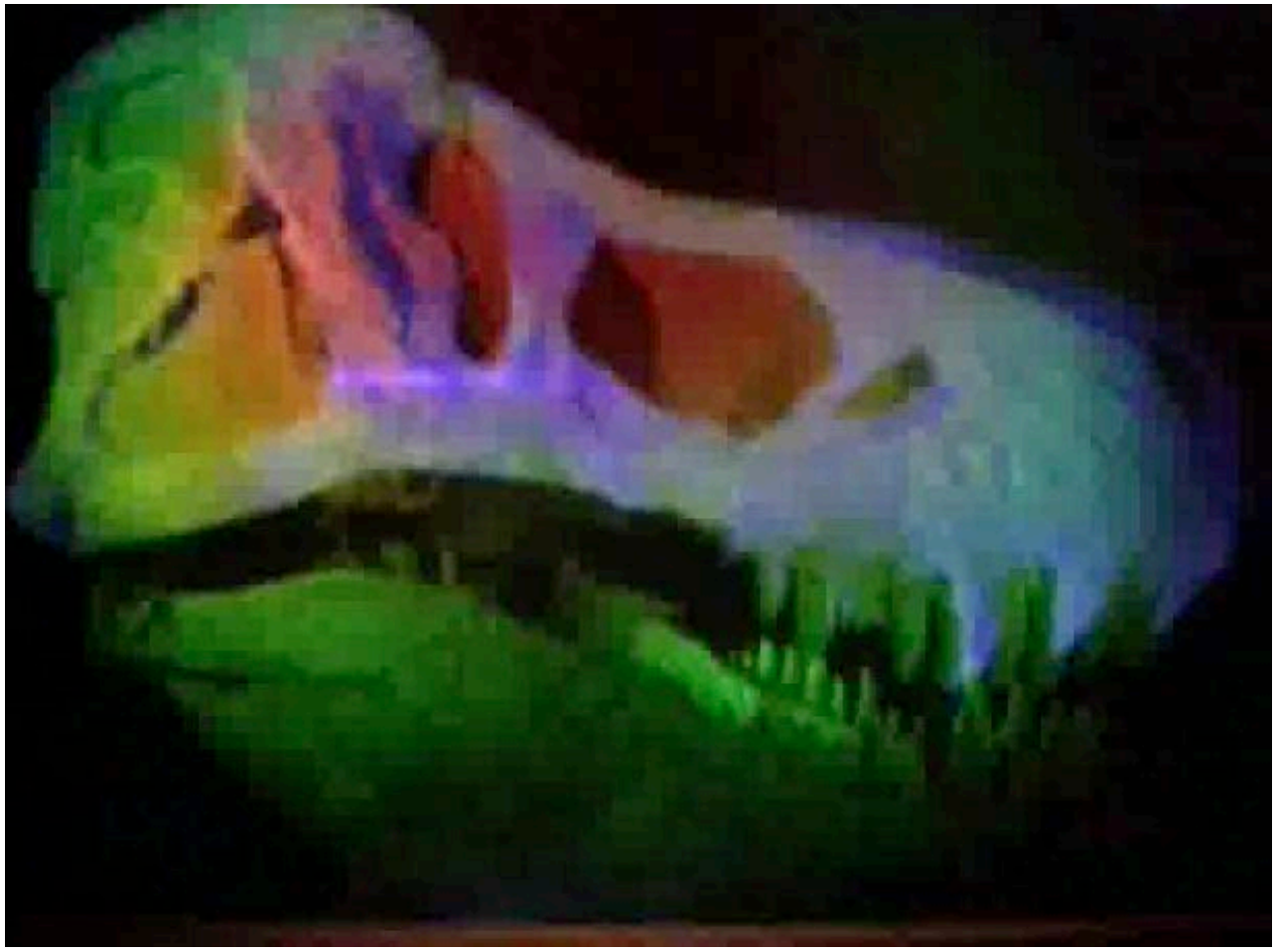




Holographics

Passive range scanning





Holographics

Active Range Scanning

Overview

- Range Scanning
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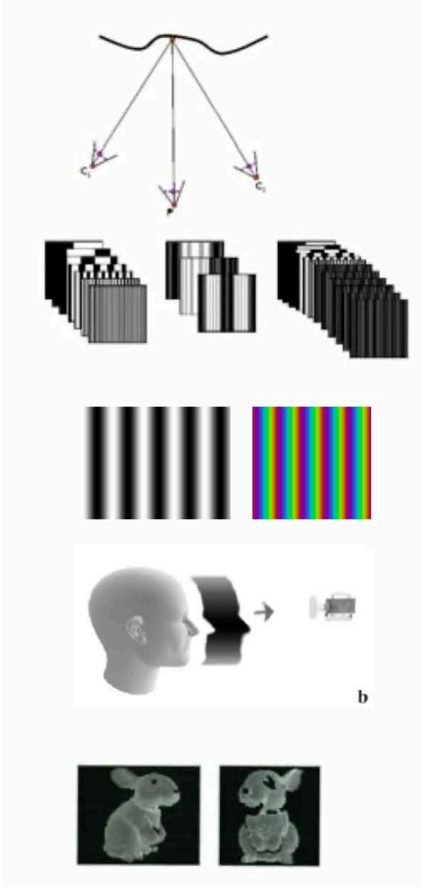
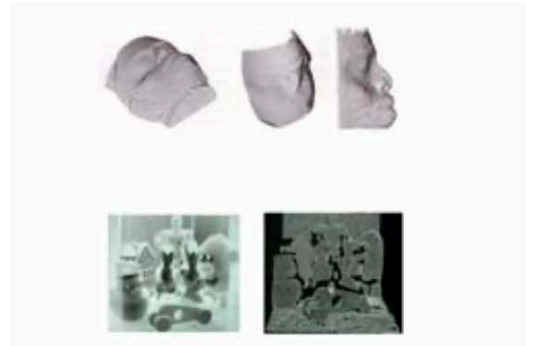
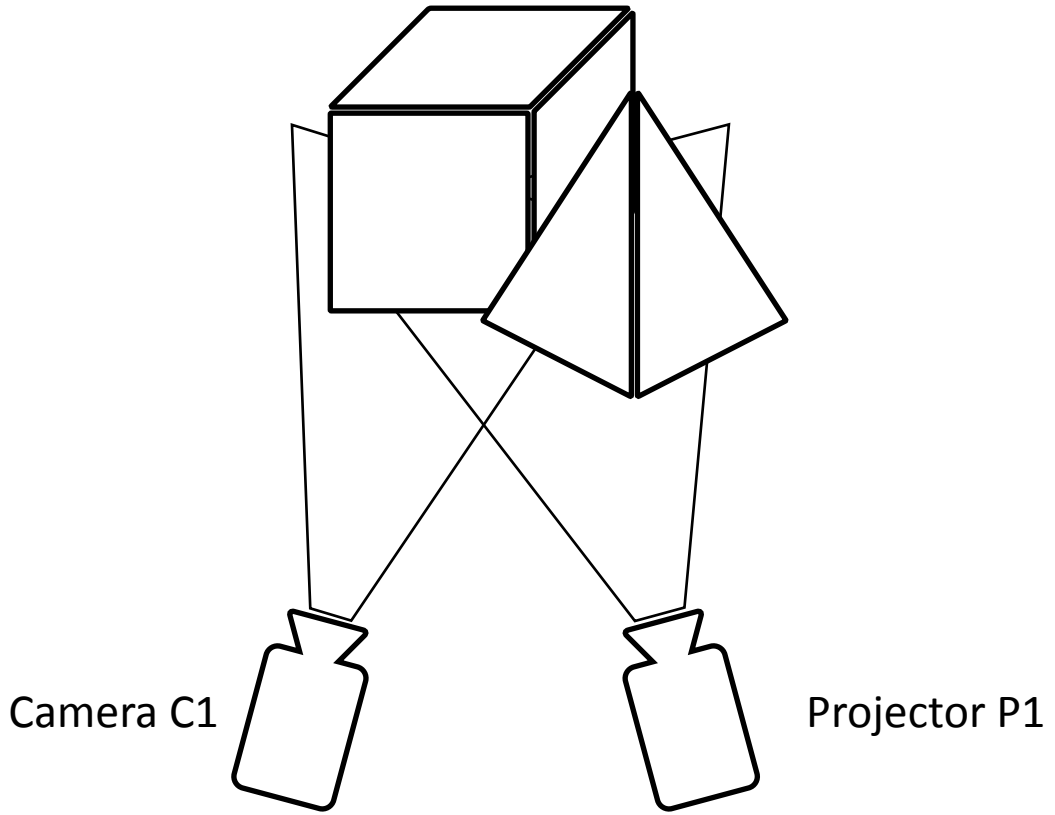




Active Range Scanning

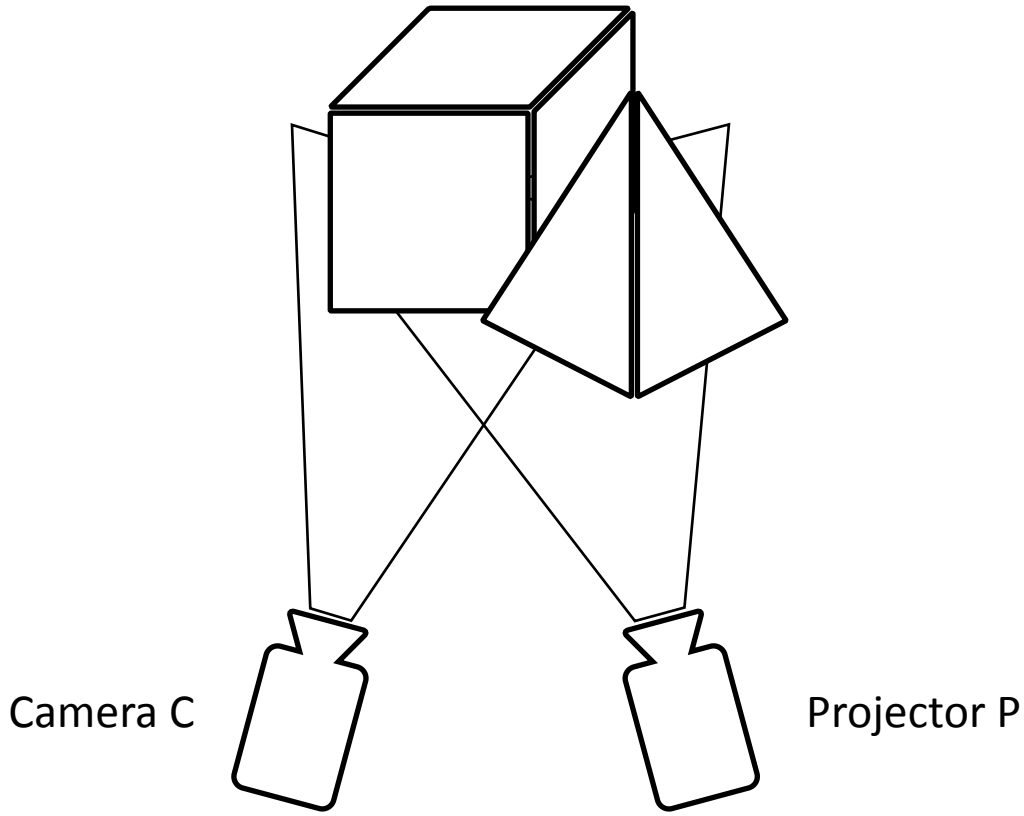
- Why active range scanning?
  - It avoids the correlation problem
- Replace one camera with a projector / light emitter
  - Structured Light Projection
  - Optical Time-of-Flight
    - Direct ToF
    - Indirect ToF

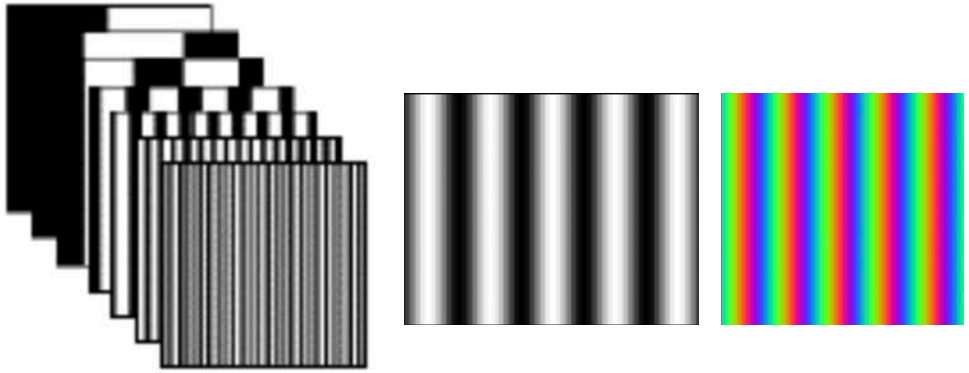


Structured Light Projection

Structured Light Projection

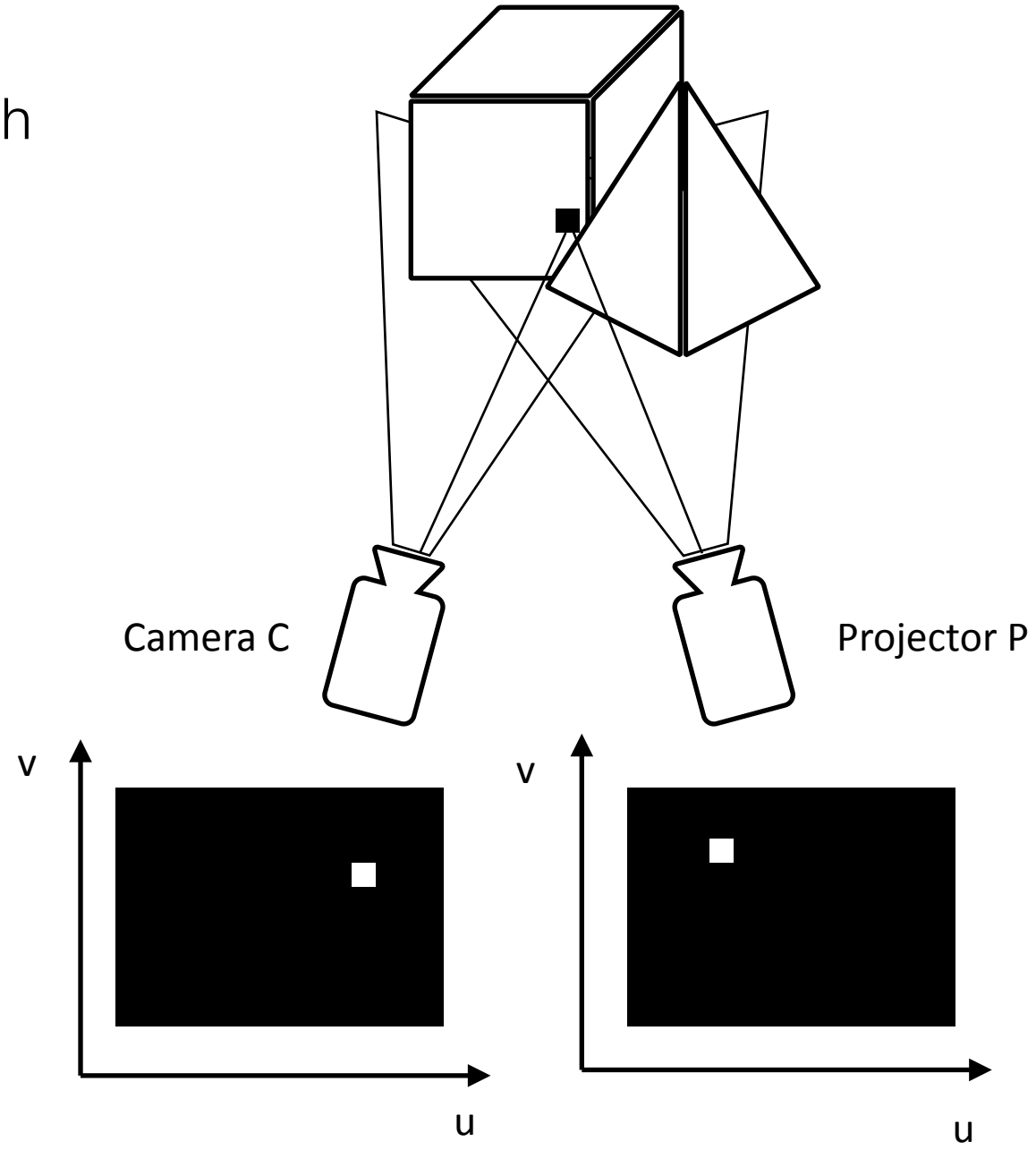
- Many structured light techniques exist that follow the two objectives:
  - Determine projector-camera correspondences with as few images as possible
  - Be robust against surface modulation and noise
- Codes include:
  - Binary codes, such as the Gray code (most common): <100 images, quite robust
  - Intensity codes that apply cosine patterns and phase shifts: 6 images, but are not robust against strong absorptions
  - Color coding: <3 images, but very fragile (does not work on coloured surfaces)





Structured Light Projection

- Let's assume 1 projector + 1 camera (both are calibrated)
- The simplest light pattern is projecting a point at $[u_P, v_P]$ that can be found at $[u_C, v_C]$. This has to be repeated for all points
- What is the problem?
  - Too slow!
- What is a better approach?



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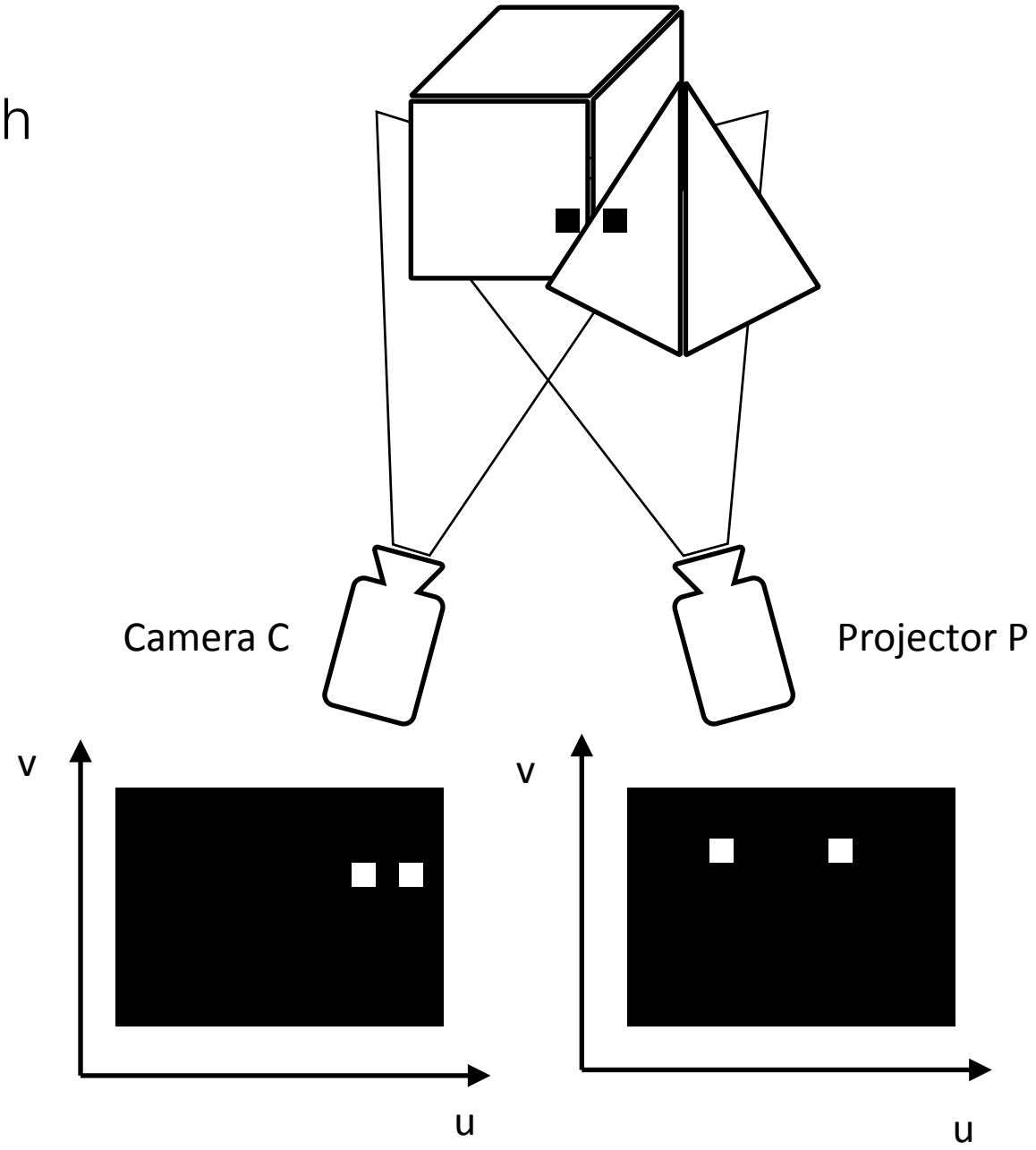
- Projecting two points!
  - But how to distinguish?



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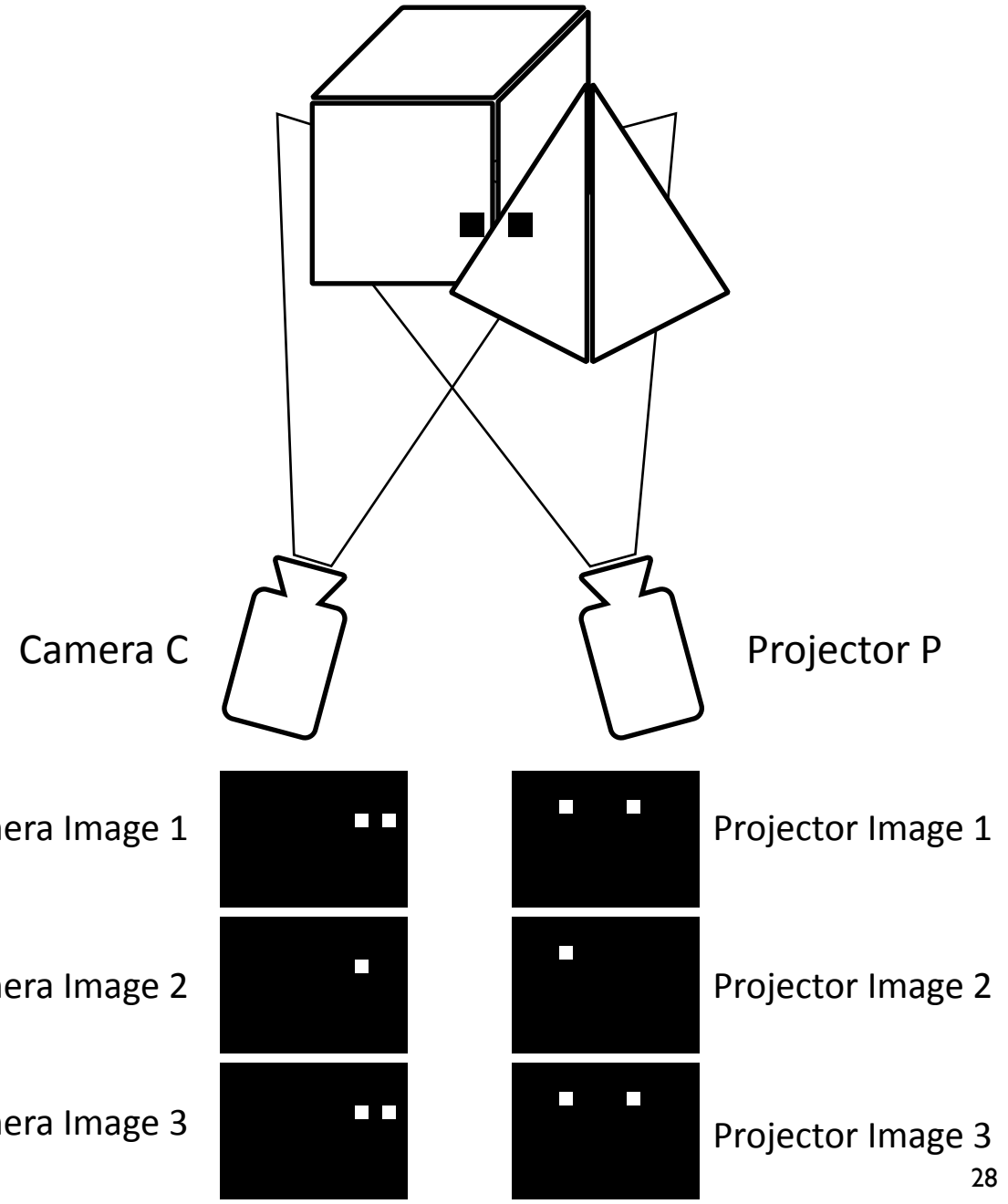
- The simplest light pattern is projecting a point at $[u_P, v_P]$ that can be found at $[u_C, v_C]$. This has to be repeated for all points
- What is the problem?
  - Too slow!
- Projecting two points!
  - Project unique "code"
- But how to scale up?

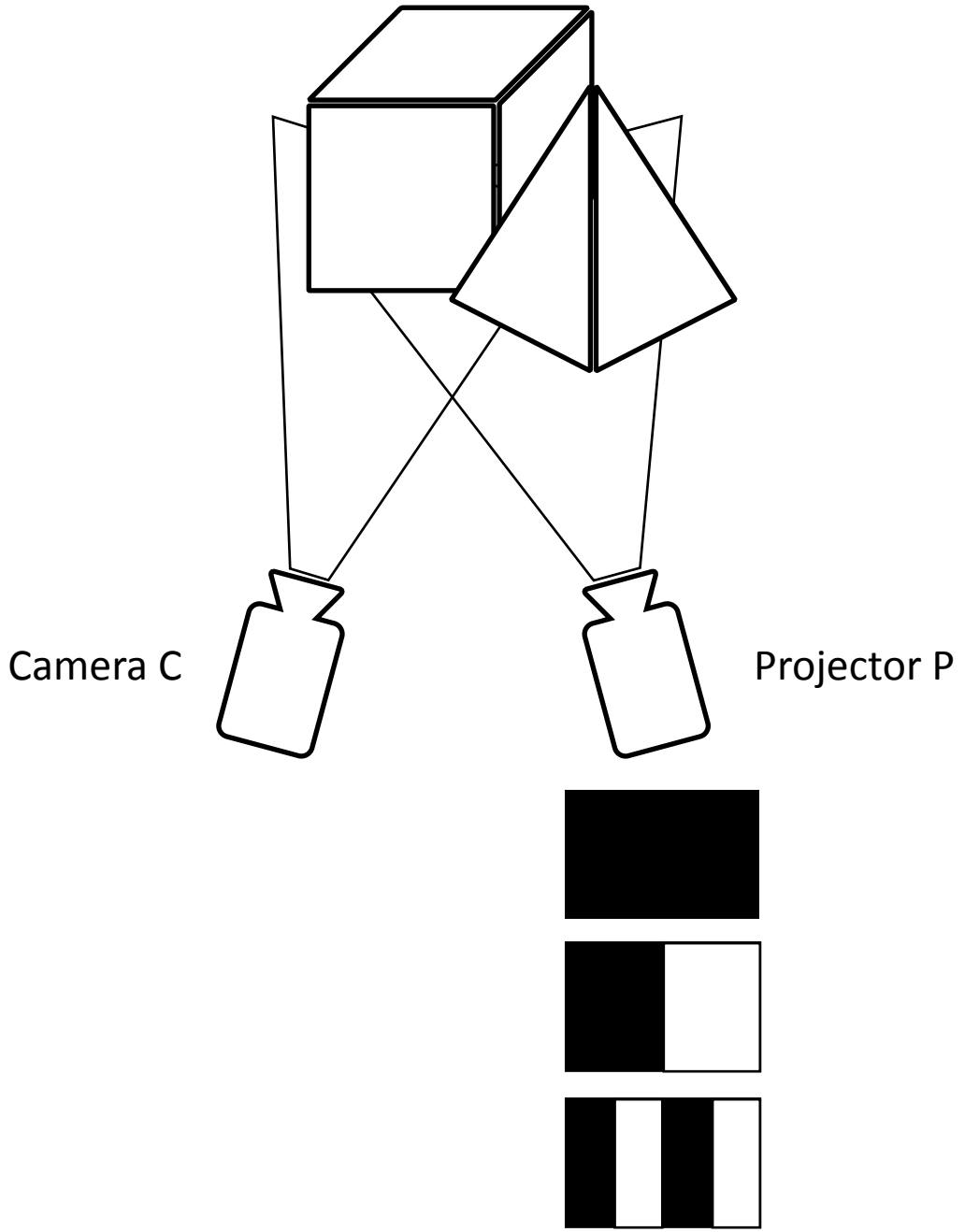


Structured Light Projection

Binary calibration

Structured Light Projection

- Let's further optimise:
  - Time multiplexing with line strip scanning
  - Each projected pixel codes a unique ID (e.g. Binary pattern)
  - How many images for 1024px resolution?



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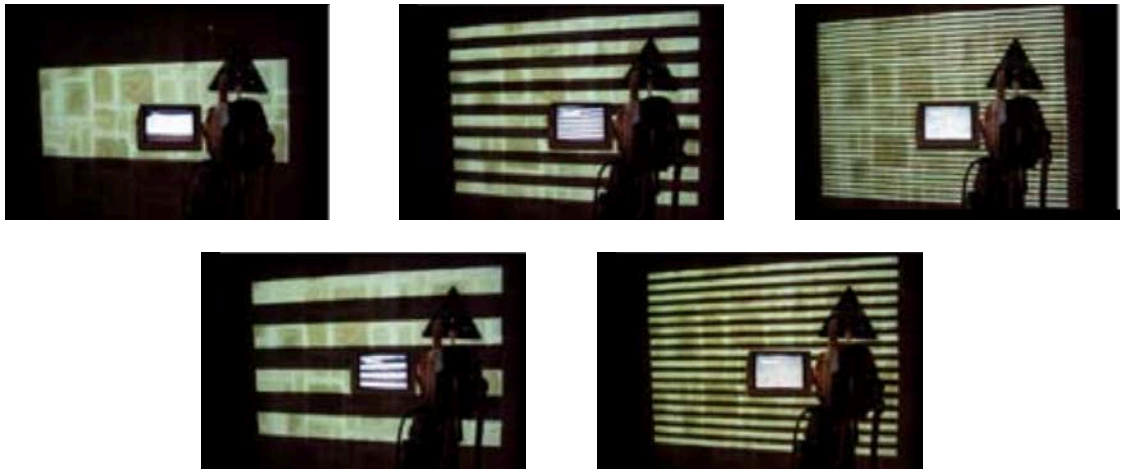
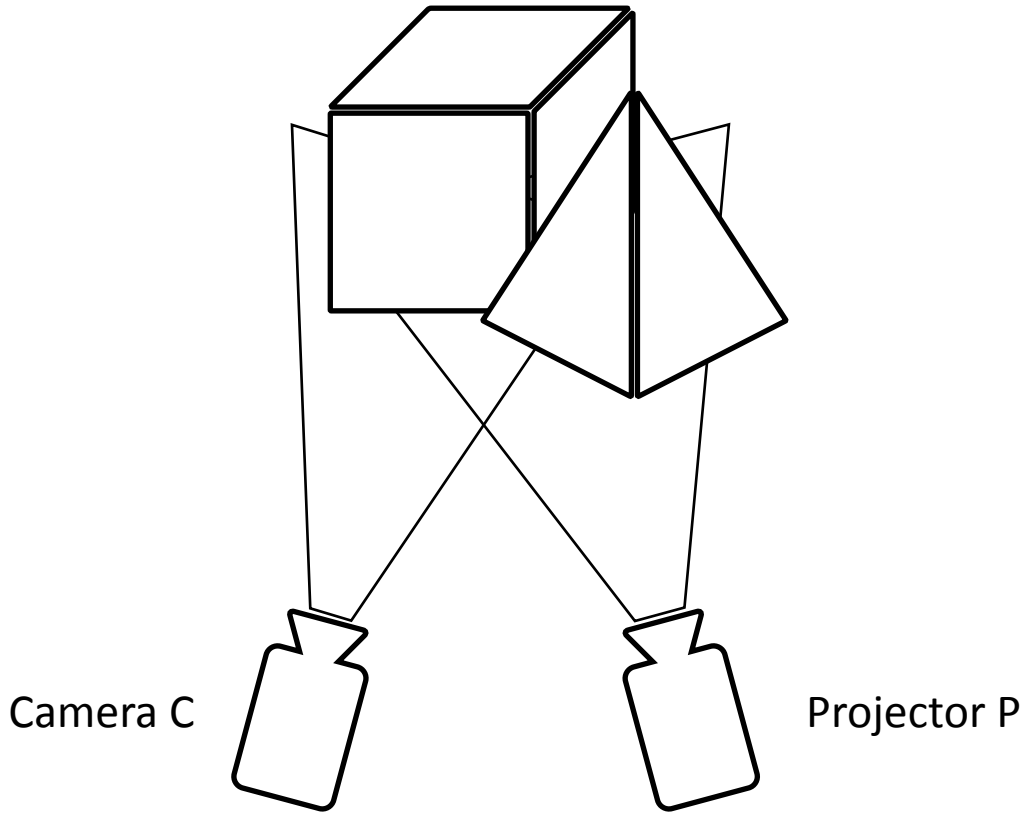
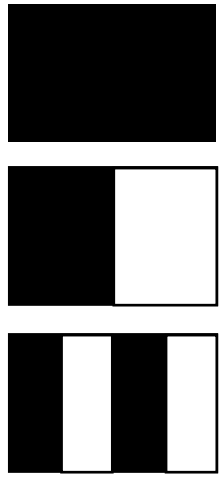


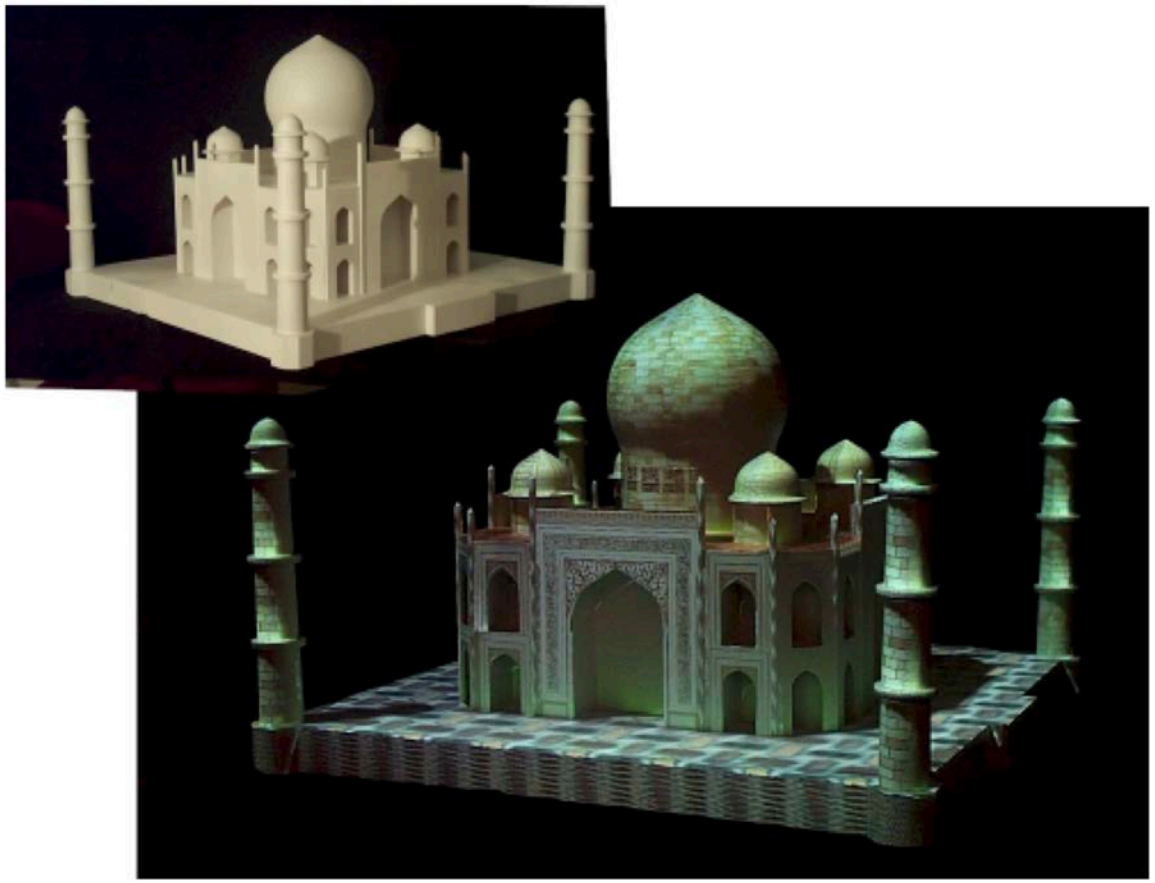


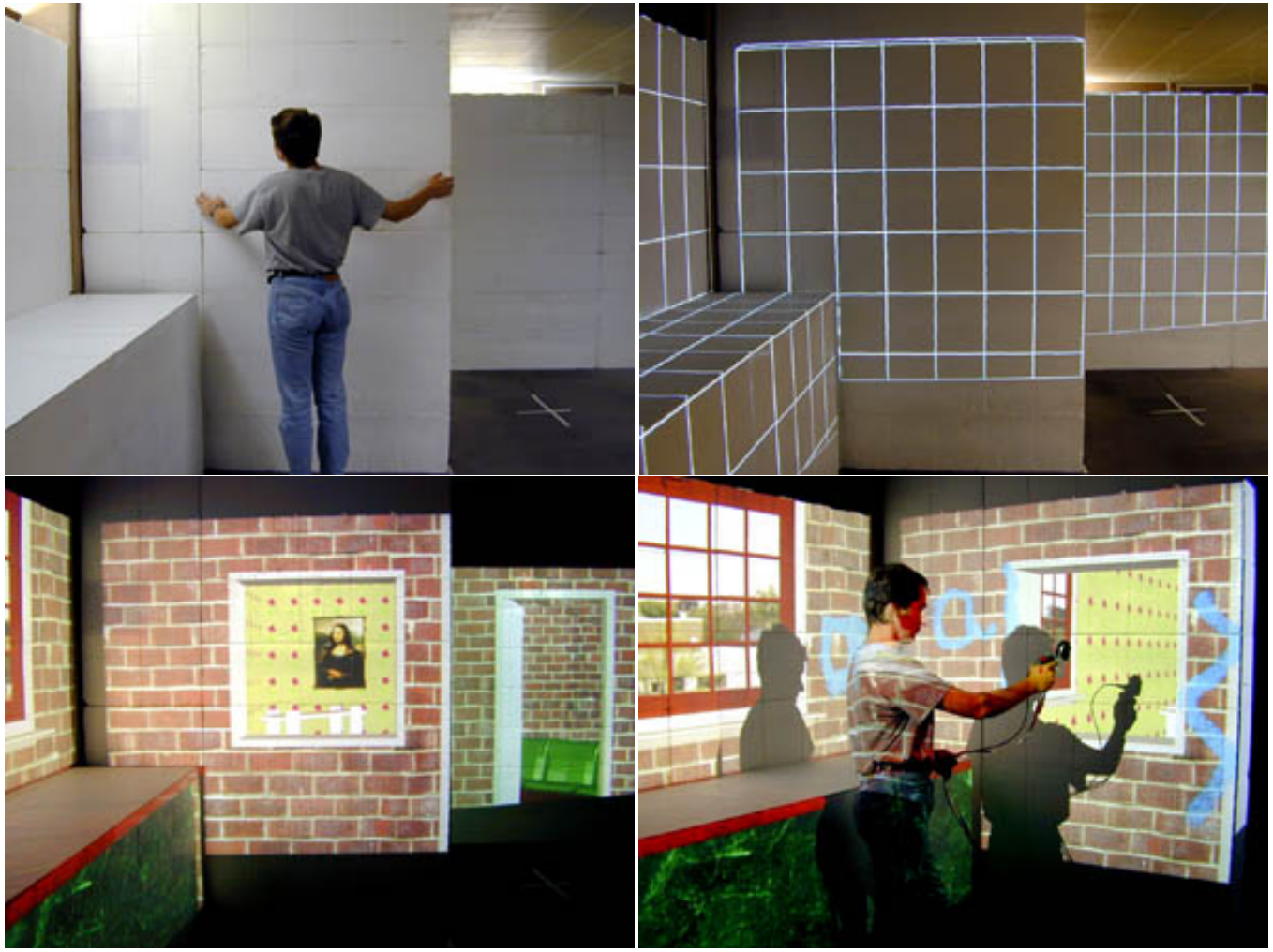


Structured Light Projection

Smart projectors

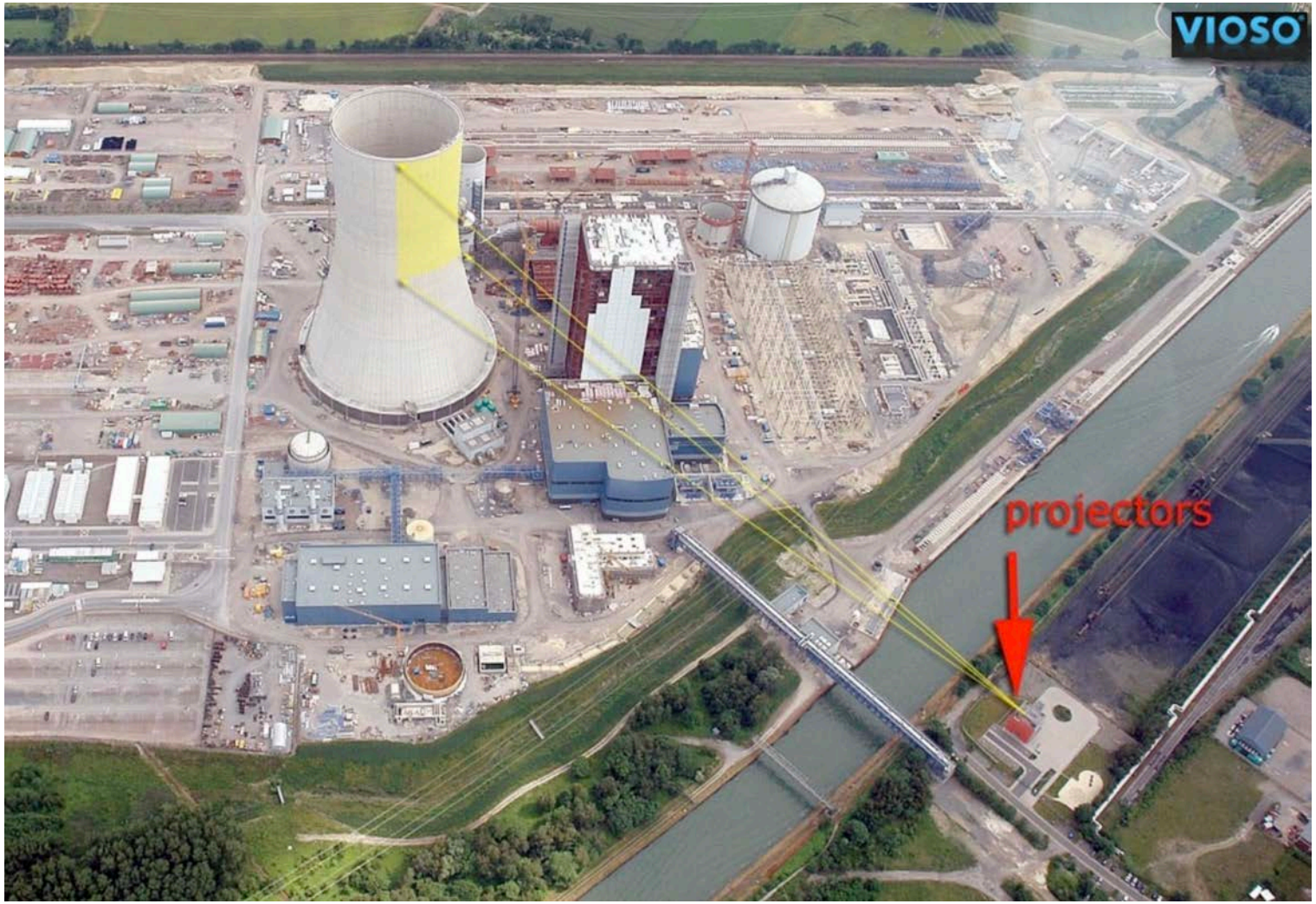
Structured Light Projection





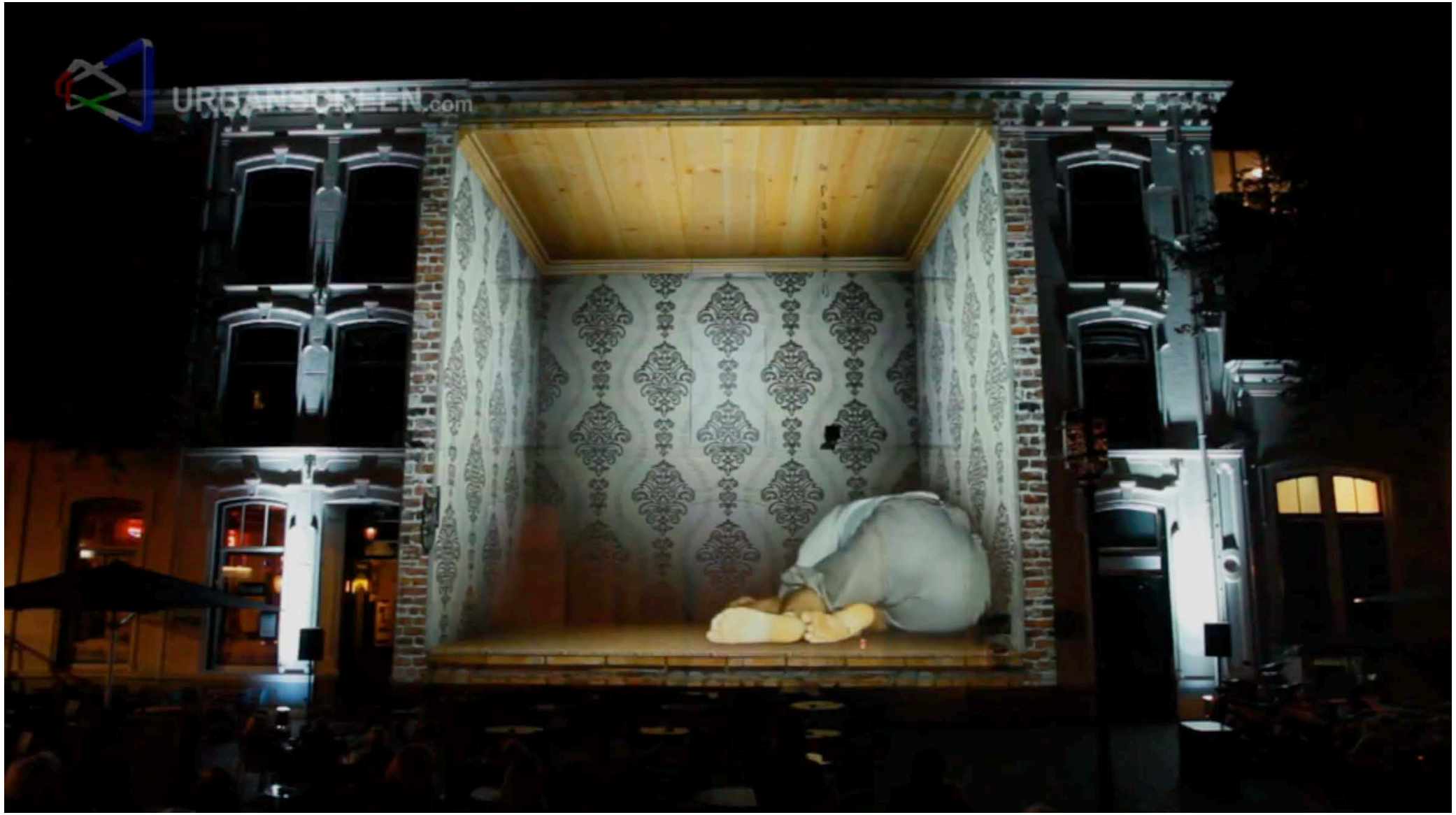
Raskat et al. “Shaderlamps”

Structured Light Projection



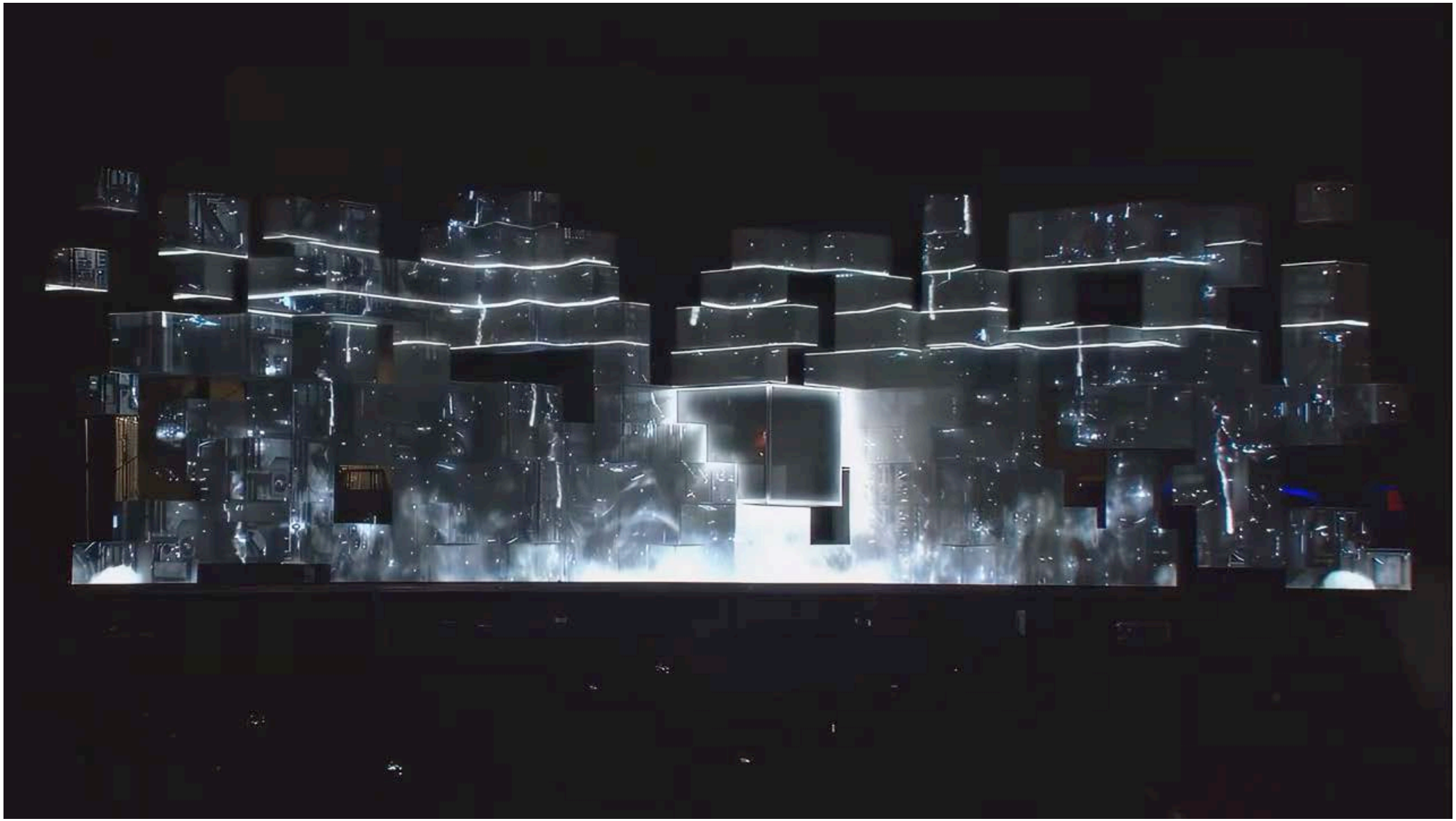
Smart projectors / Vioso

Structured Light Projection



Smart projectors / Vioso

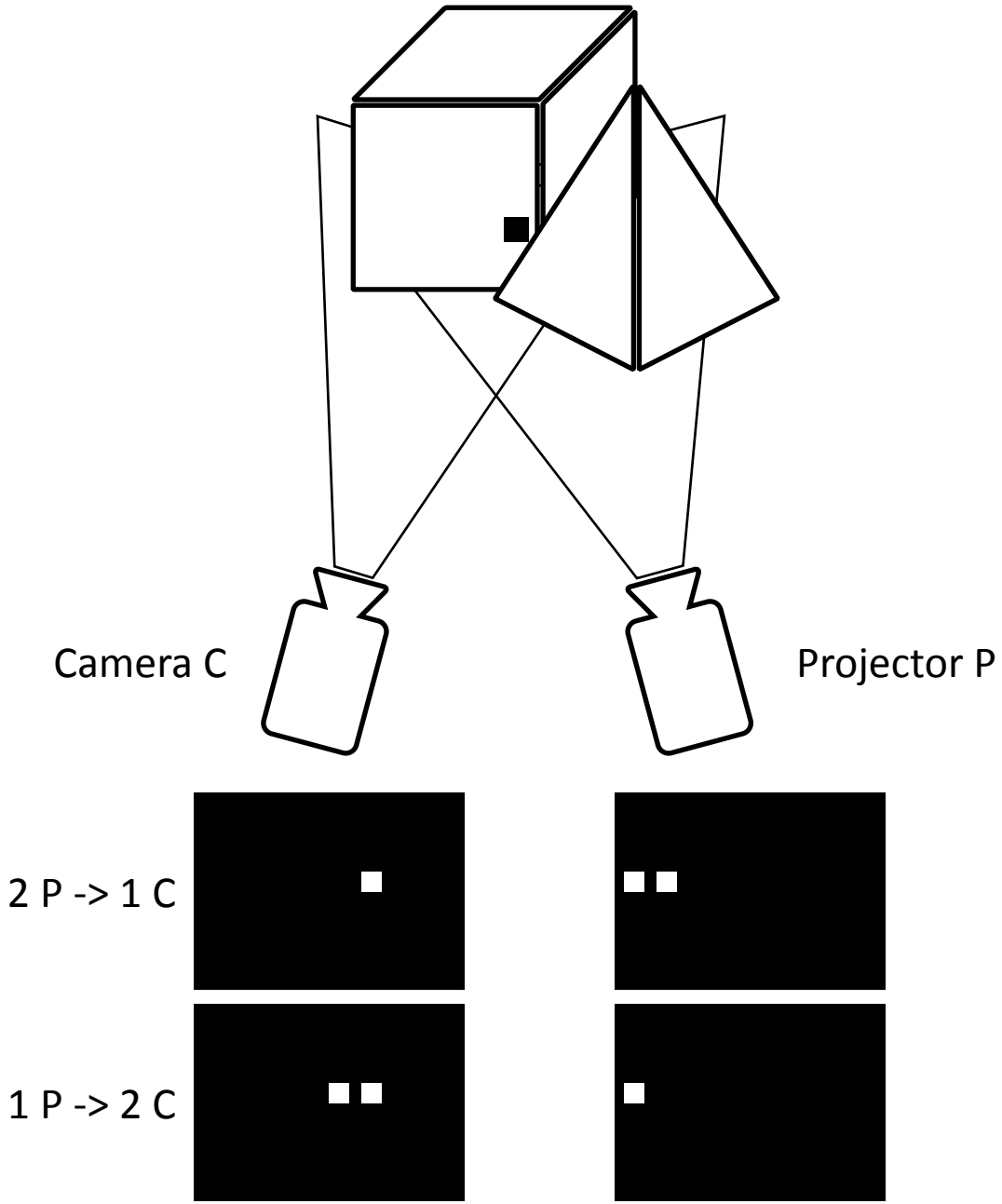
Structured Light Projection



Amob Tobin

Structured Light Projection

- Other issues:
  - Results usually not in 1-to-1 mappings!
    - Multiple projector pixels can map on same camera pixels / multiple camera pixels can be addressed by single projector pixel
  - Solution?
    - Multiple entries must be averaged



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  - Solution?
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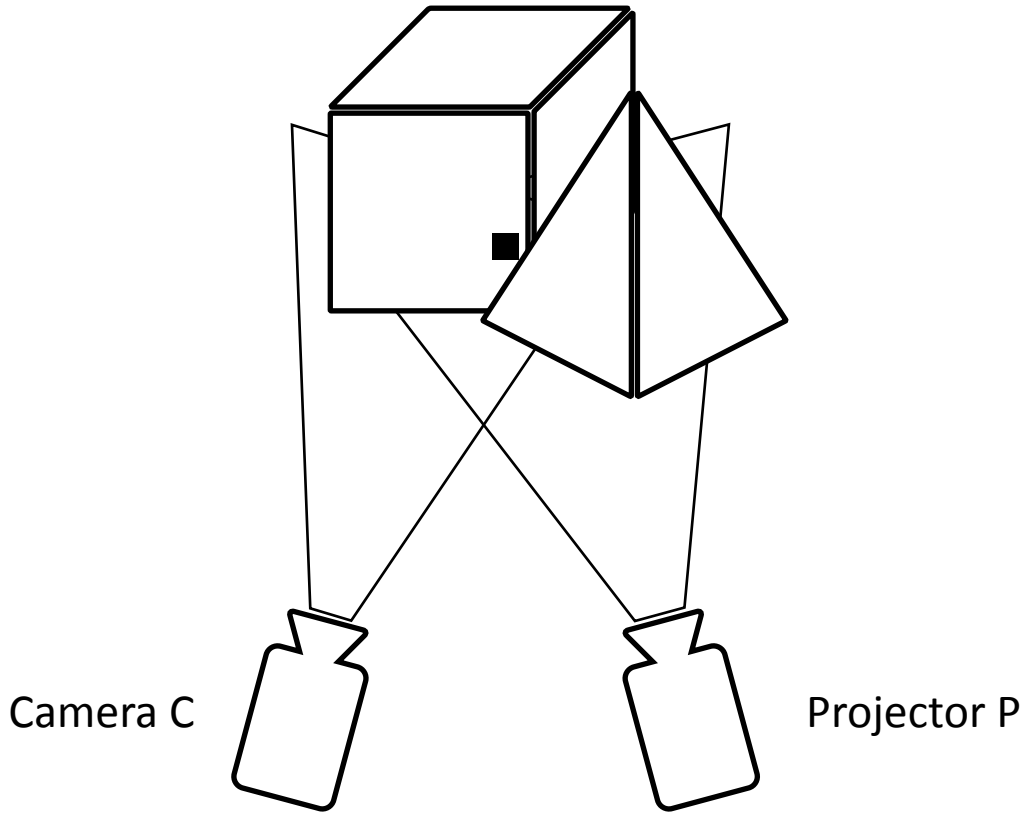
- Any other ideas for improvements?



Structured Light Projection

- Other issues:
  - Results usually not in 1-to-1 mappings!
    - Multiple projector pixels can map on same camera pixels / multiple camera pixels can be addressed by single projector pixel
  - Solution?
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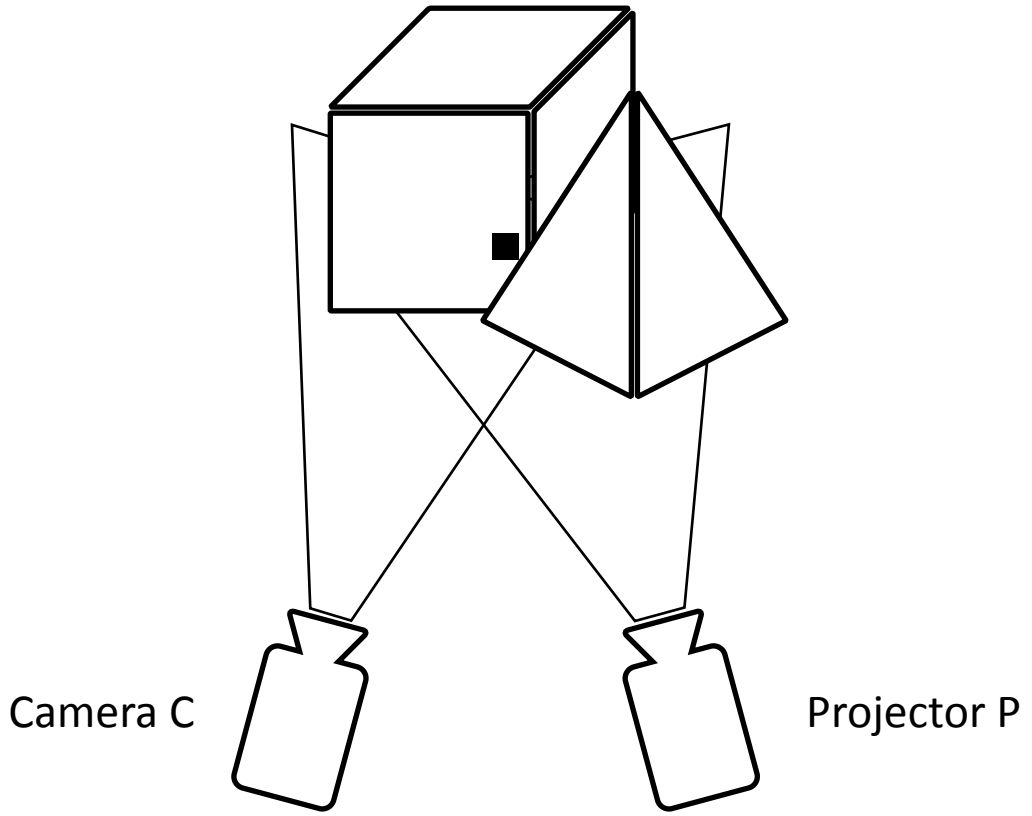
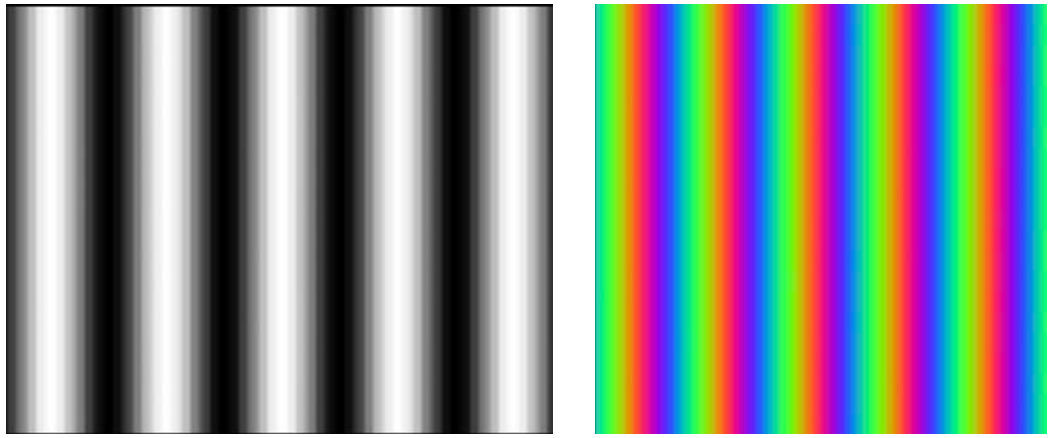
- Any other ideas for improvements?
  - Encode more information into structured projection
  - For example: colours and intensities





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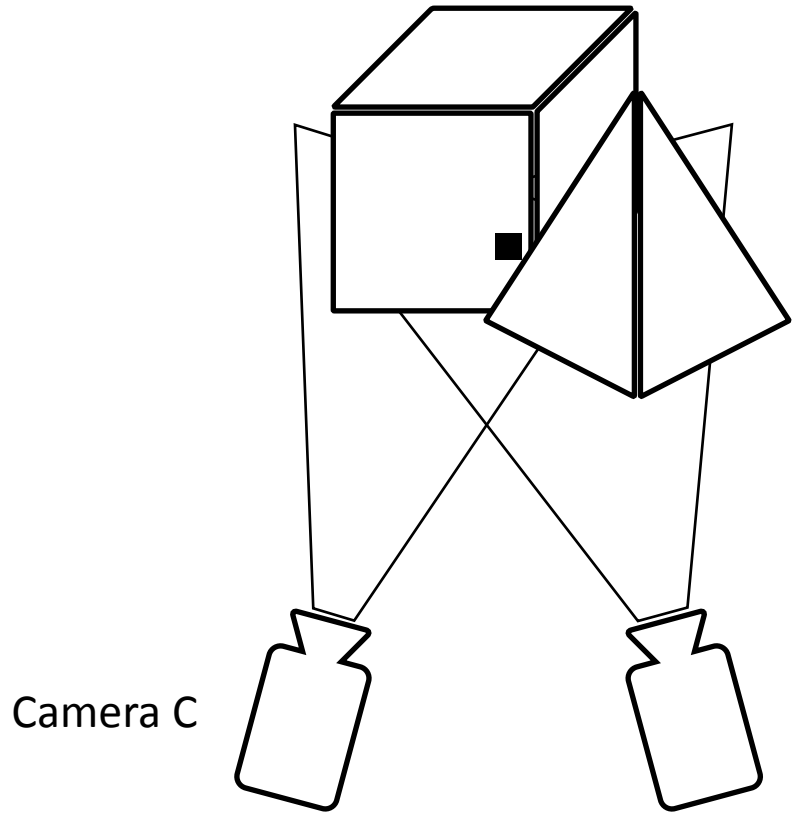
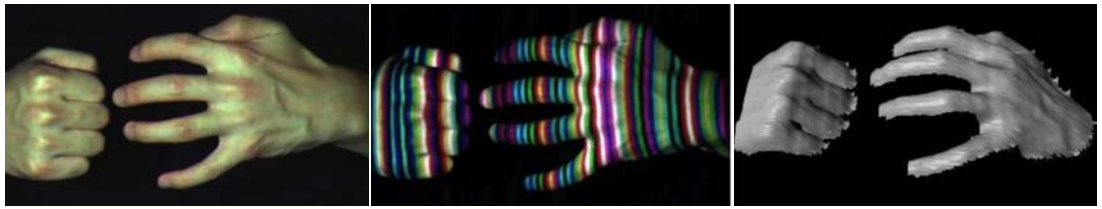
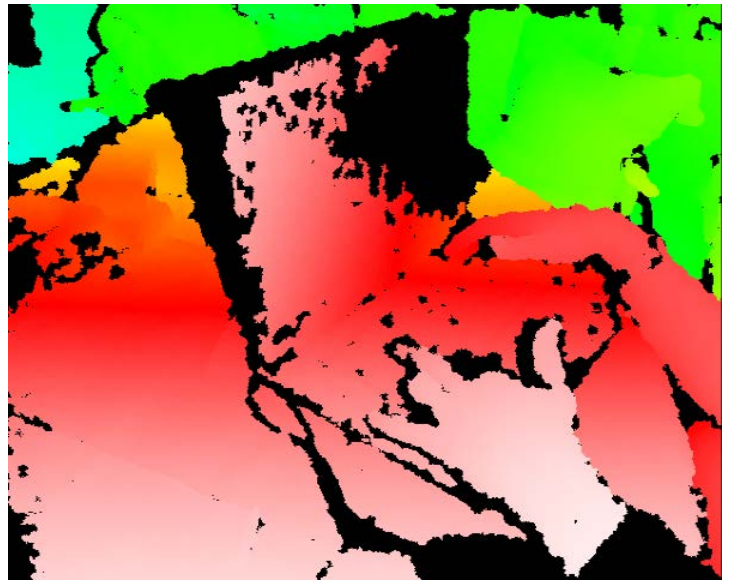




Structured Light Projection

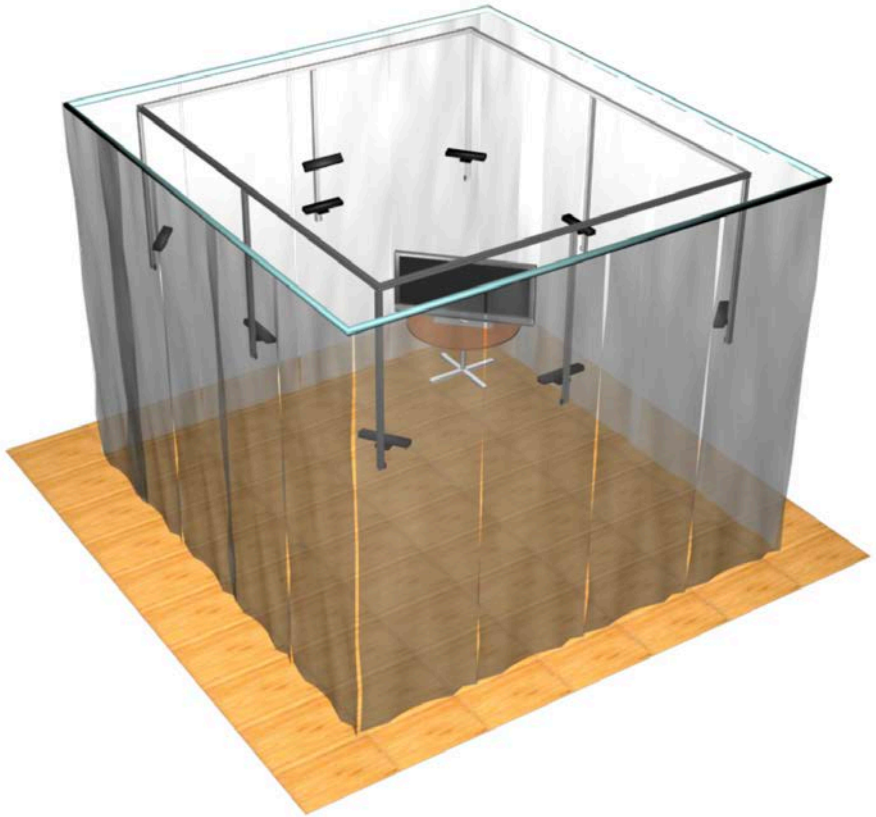
https://fts.gr/structured-light-3d-scanner/

Structured Light Projection



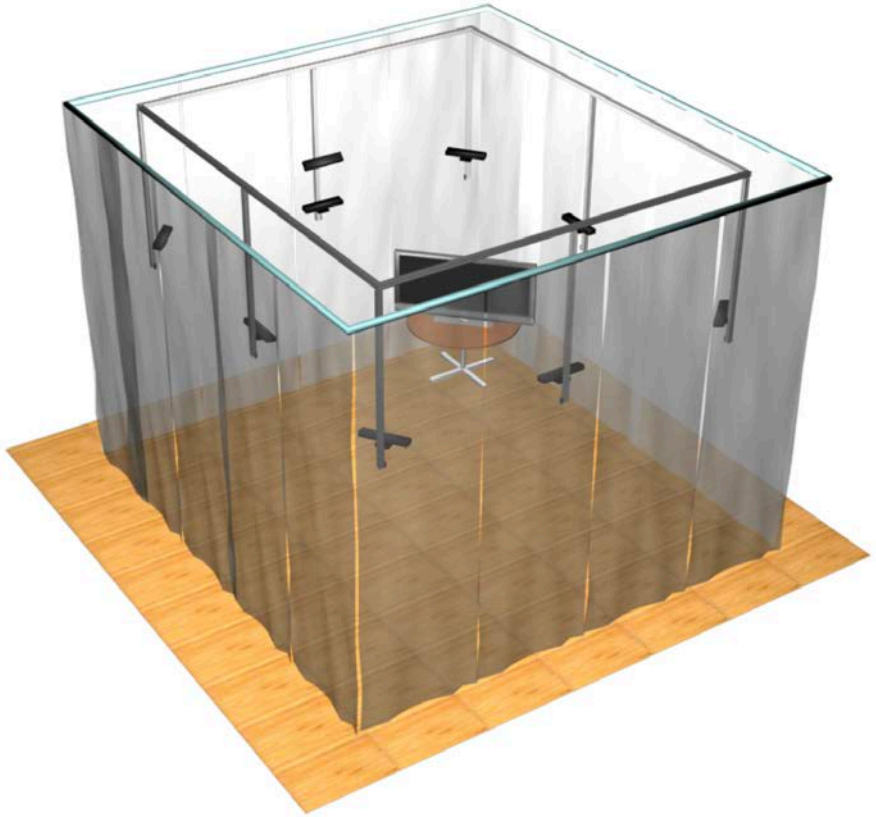
MS Kinect 1 (PrimeSense sensor, not MS Kinect 2 uses ToF discussed later)

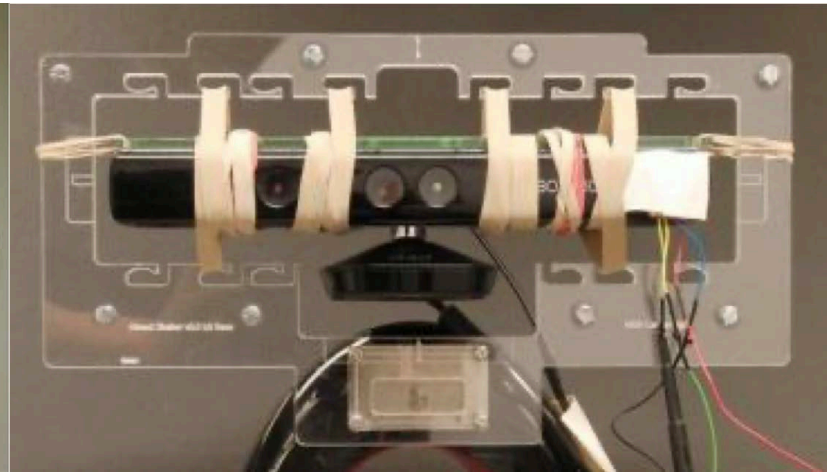
Structured Light Projection



Maimone and Fuchs “Reducing Interference Between Multiple Structured Light Depth Sensors Using Motion”

Structured Light Projection





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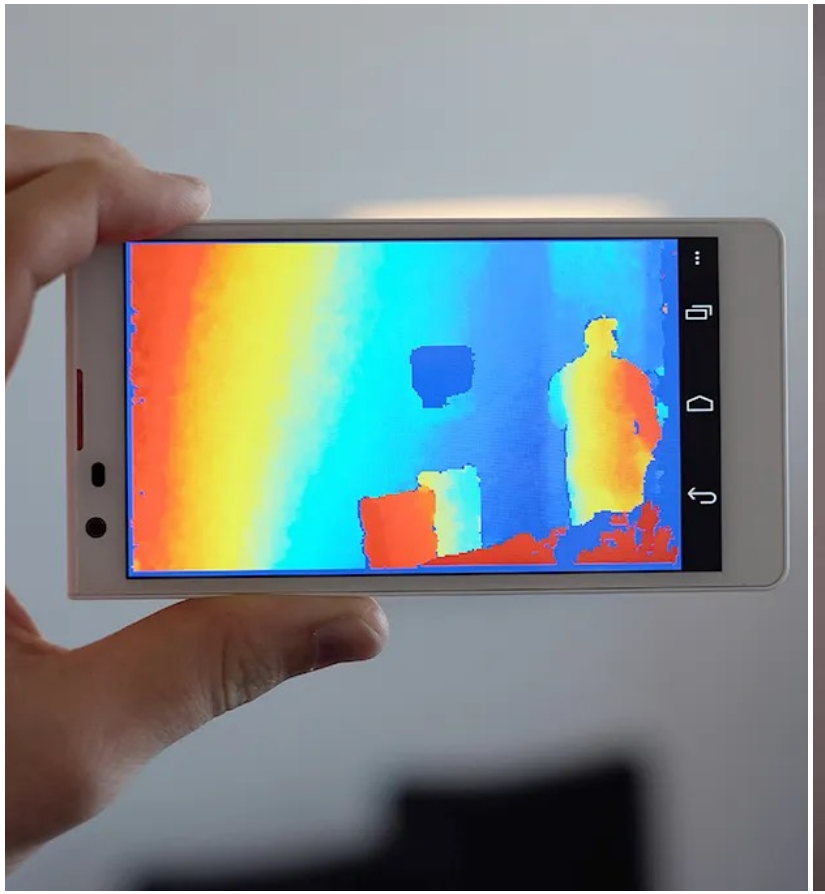
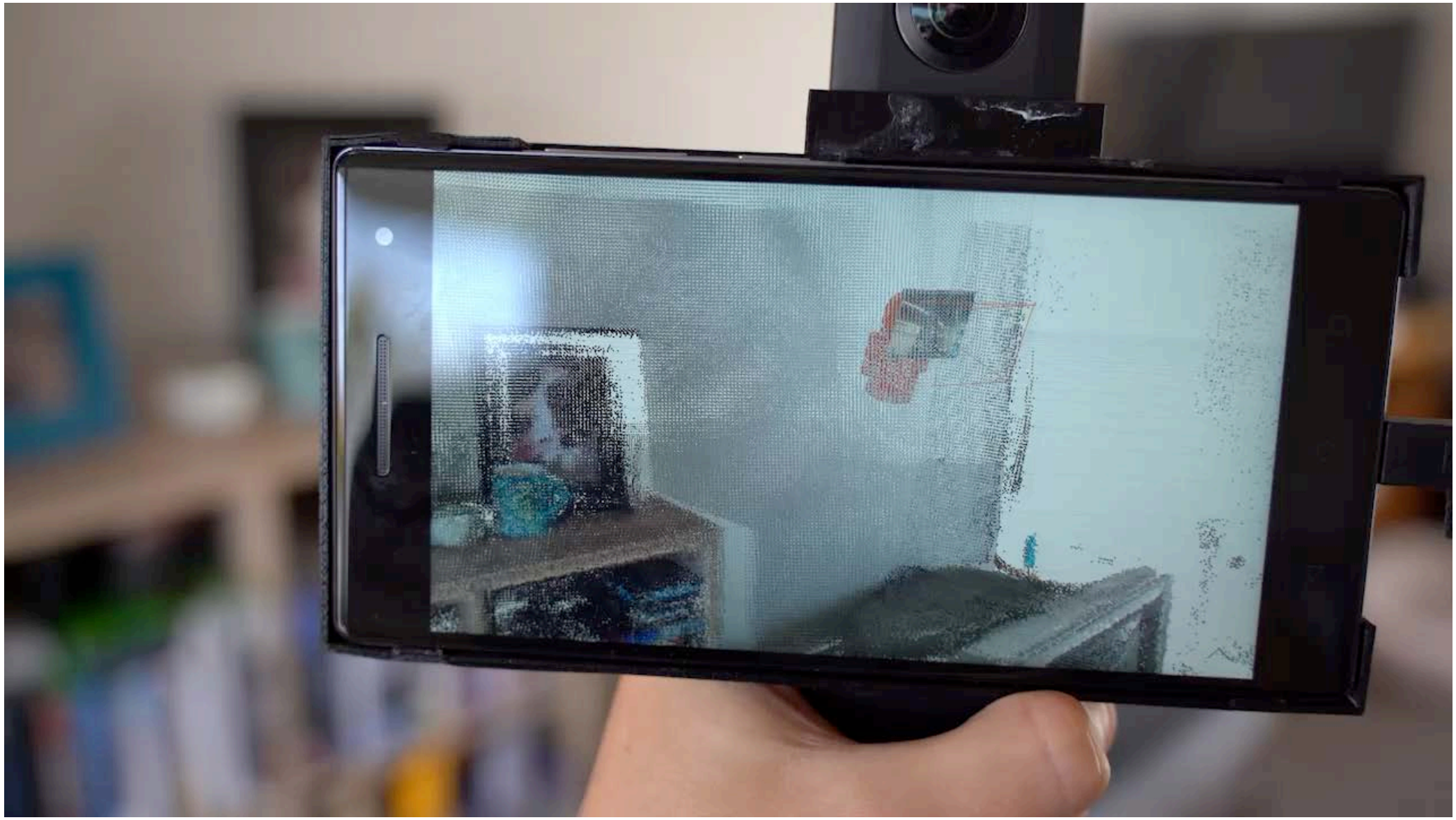


Google Project Tango (also using ToF discussed later)

Structured Light Projection

Mobile Portation

Structured Light Projection

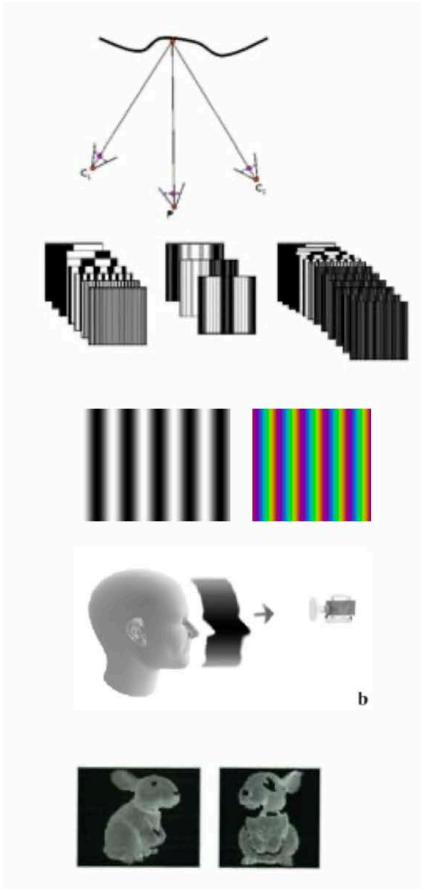


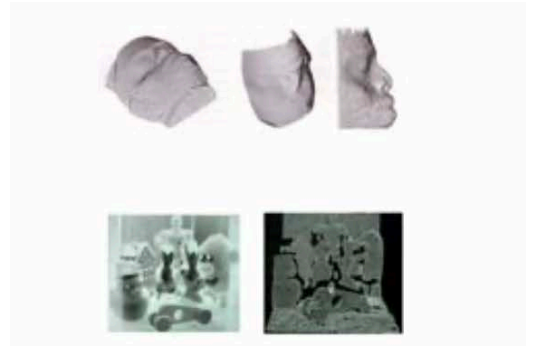
Mobile Portation

Time of Flight (ToF)

Overview

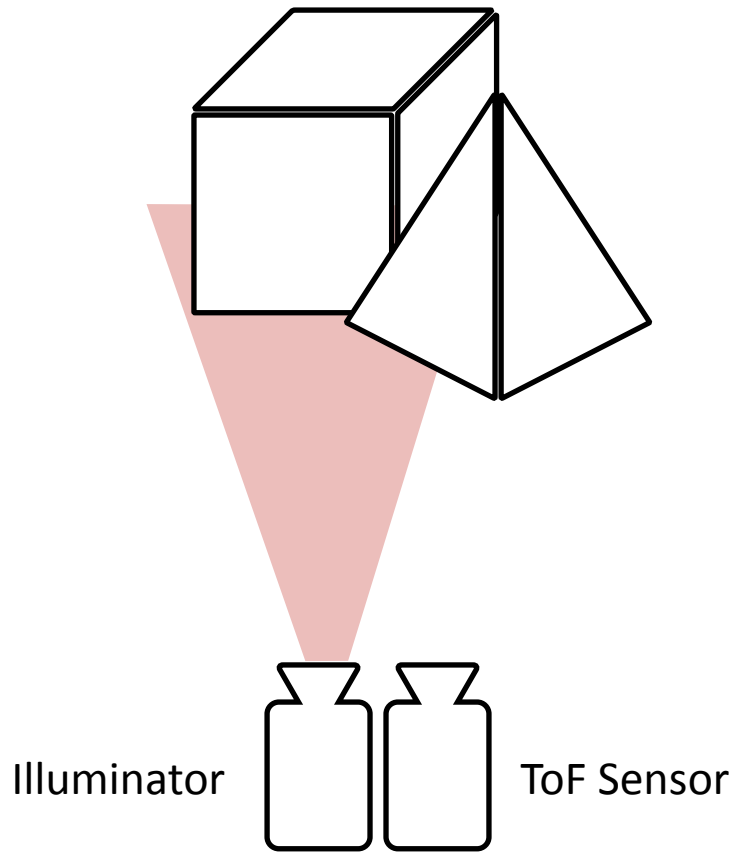
- Range Scanning
  - Passive:
    - Stereo or Multi-Camera
  - Active:
    - Structured Light Projection
    - Optical Time-of-Flight
      - Direct ToF
      - Indirect ToF
- Registration of Depth Maps
- Processing Depth Maps





Optical Time-of-Flight (ToF)

- General idea:
  - Compute depth by round-trip estimation of a light wave emitted and its reflection back to the sensor
  - $D = C \cdot \Delta t/2$
- Use low-power IR illumination for pulsed illumination
  - Can be switched on/off with <1ns
  - Generates a “light wall” that is reflected back by objects



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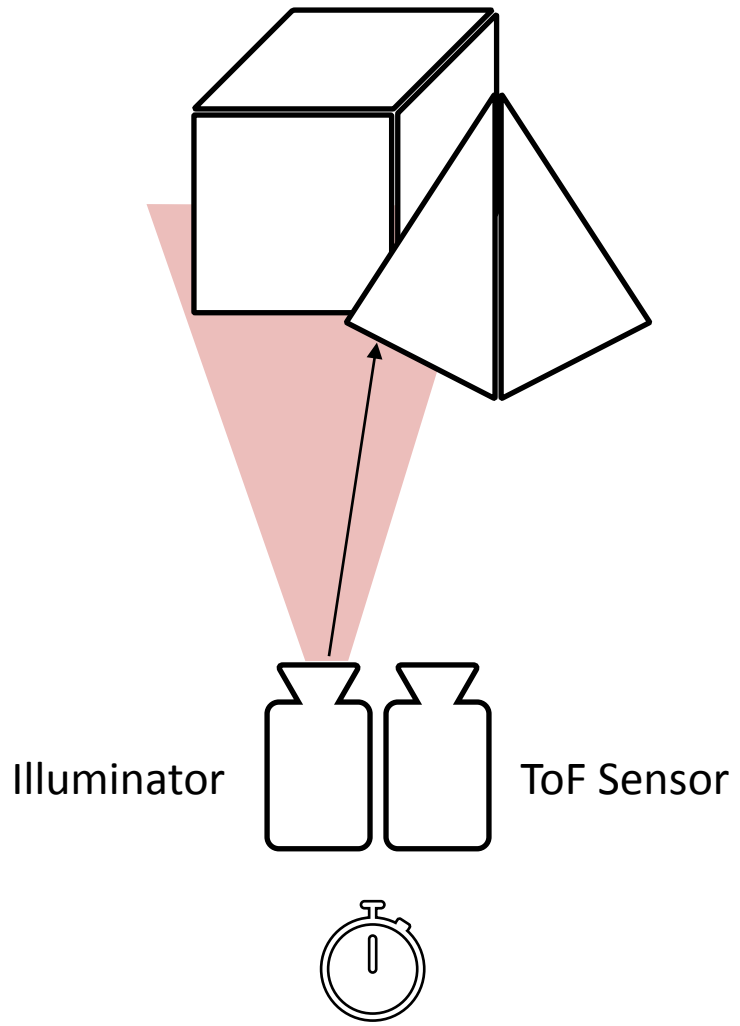

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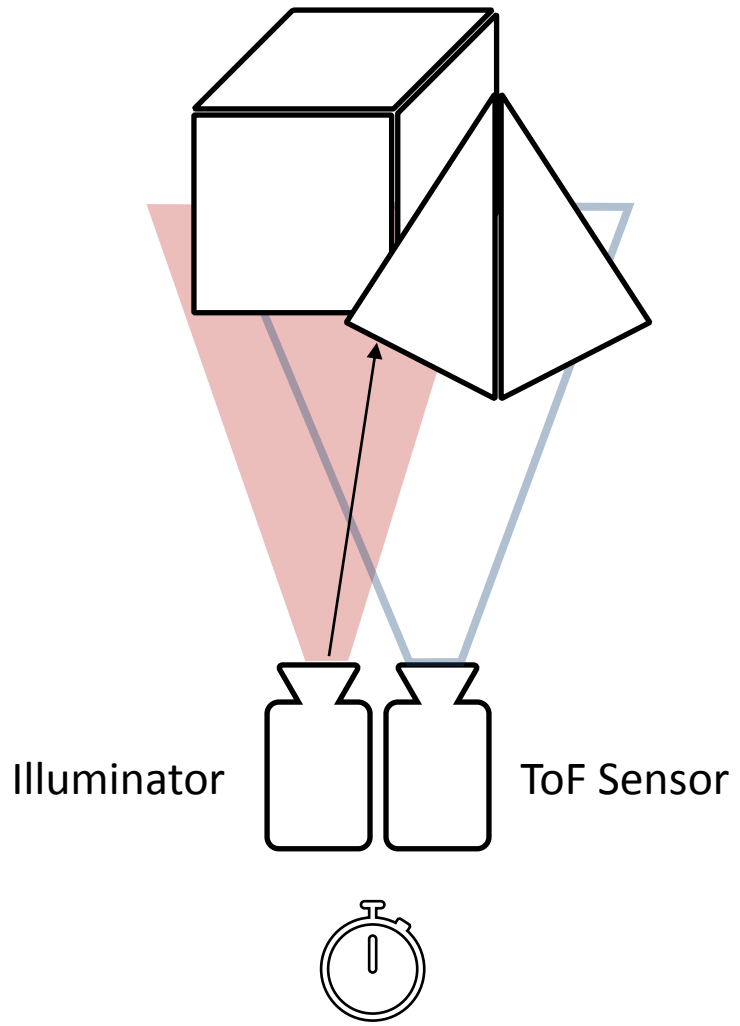

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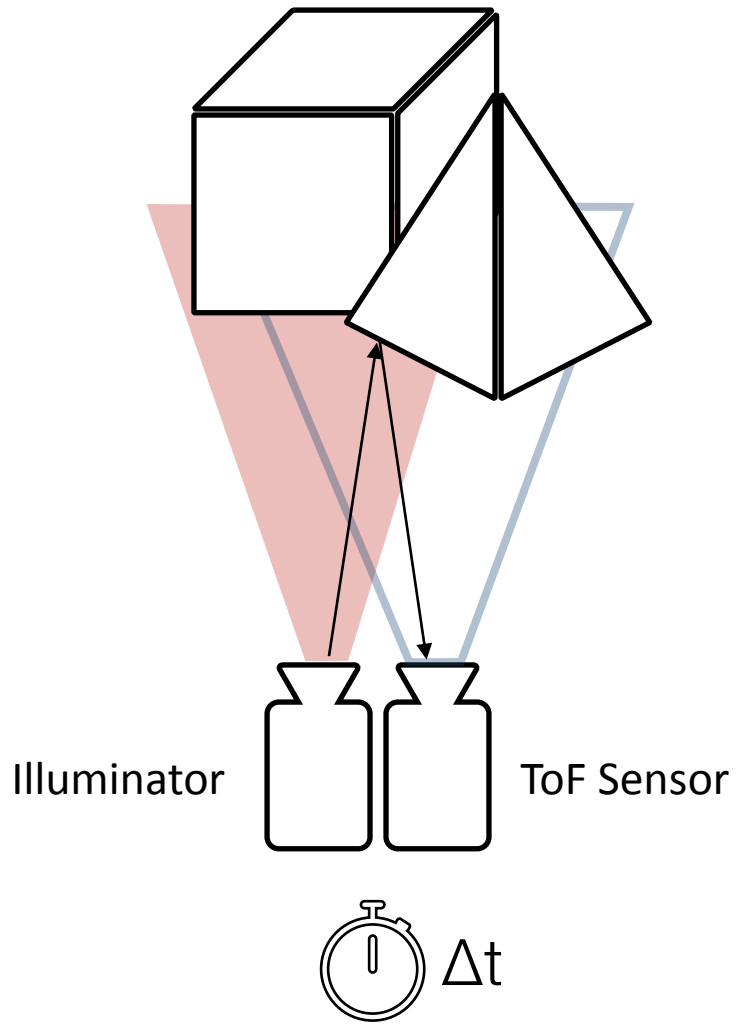

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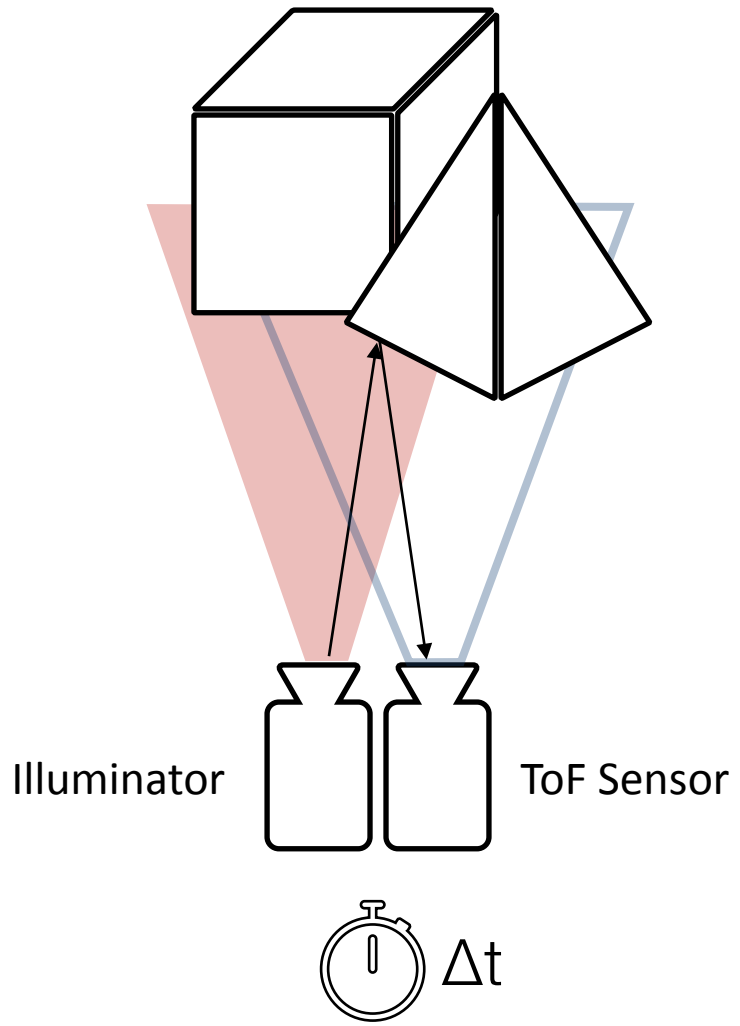

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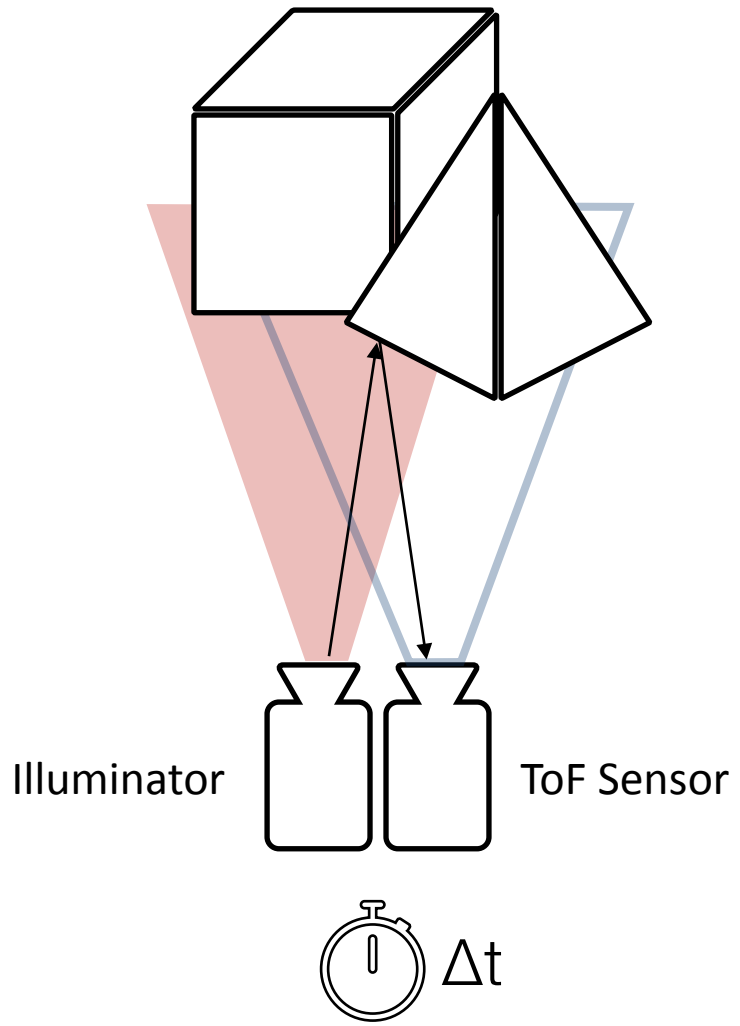
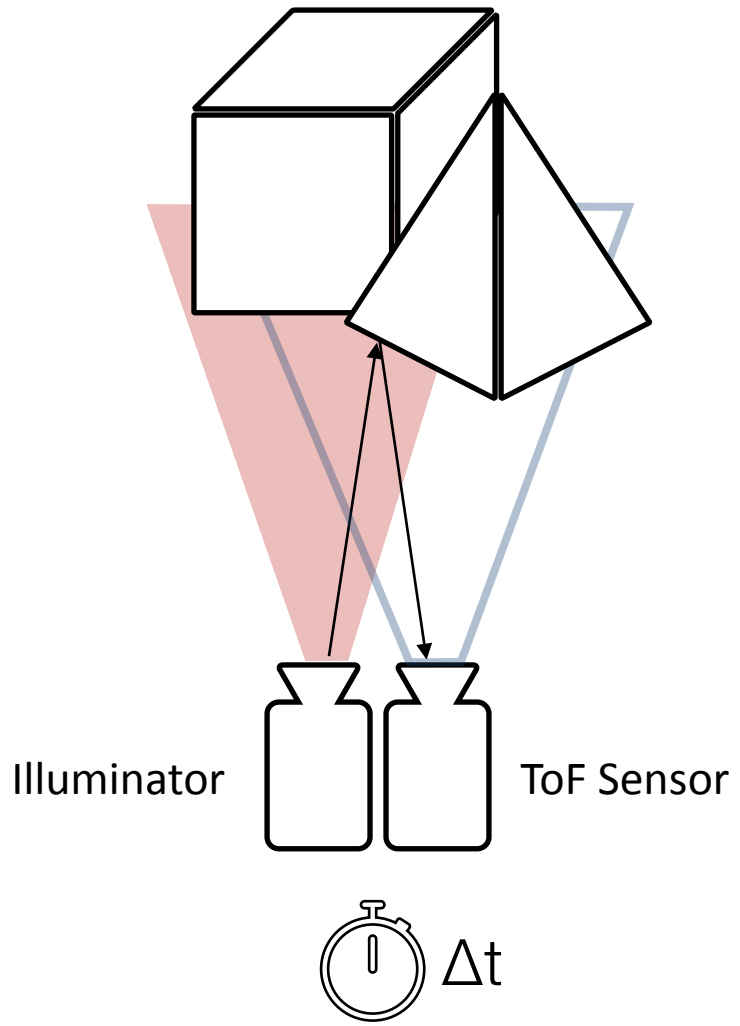
  - 3.3 picoseconds for light to travel 1 millimeter



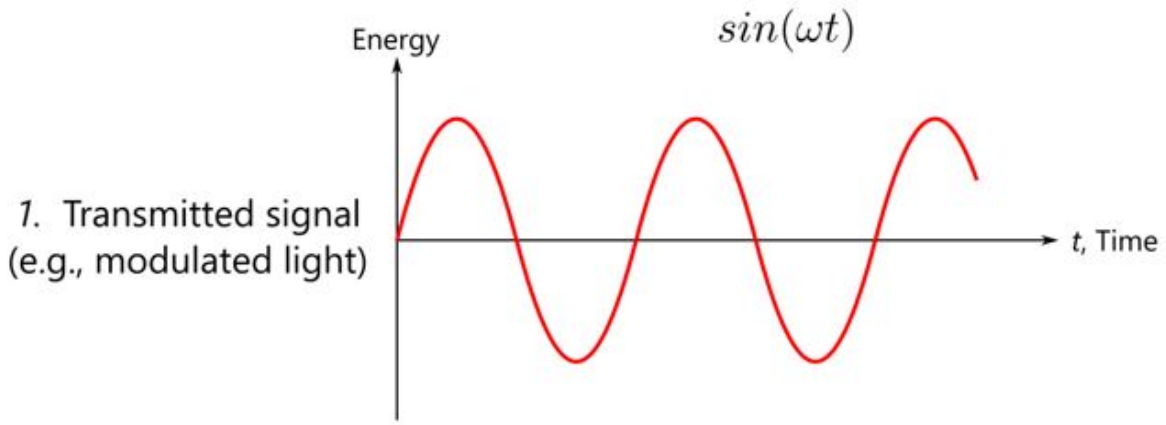
Optical Time-of-Flight (ToF)

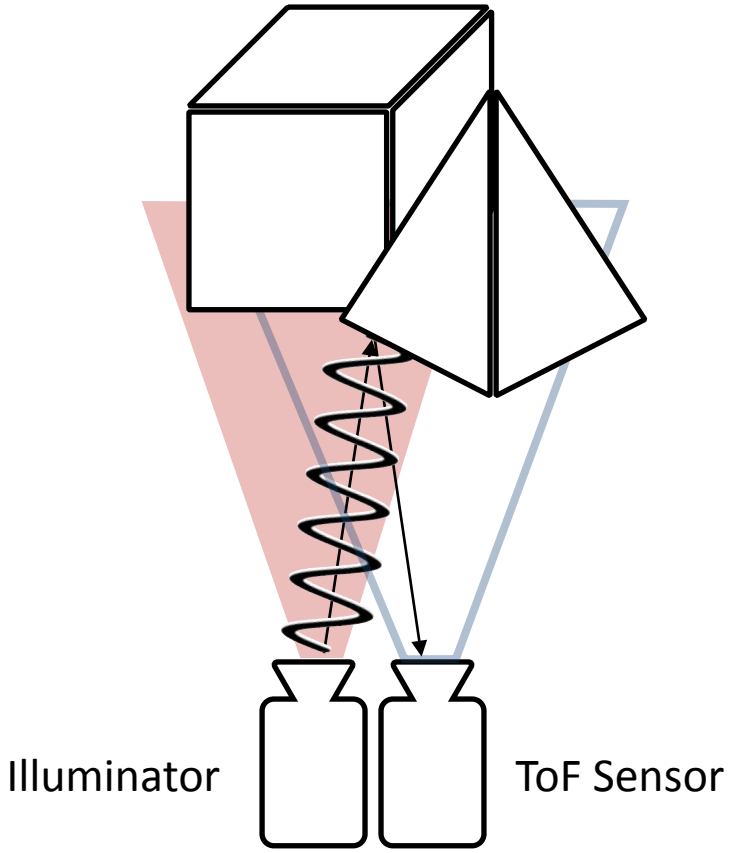
- Practical realisation:
  - Direct Time of Flight
    - Measuring actual round-trip of light pulse
    - Technical limits to measuring time affect accuracy
  - Indirect Time of Flight
    - Indirectly measuring round-trip of light pulse
    - Usually utilising phase information



Indirect Time-of-Flight (ToF)

- We emit light with a periodic pattern, then calculate the phase shift in the return measurement.





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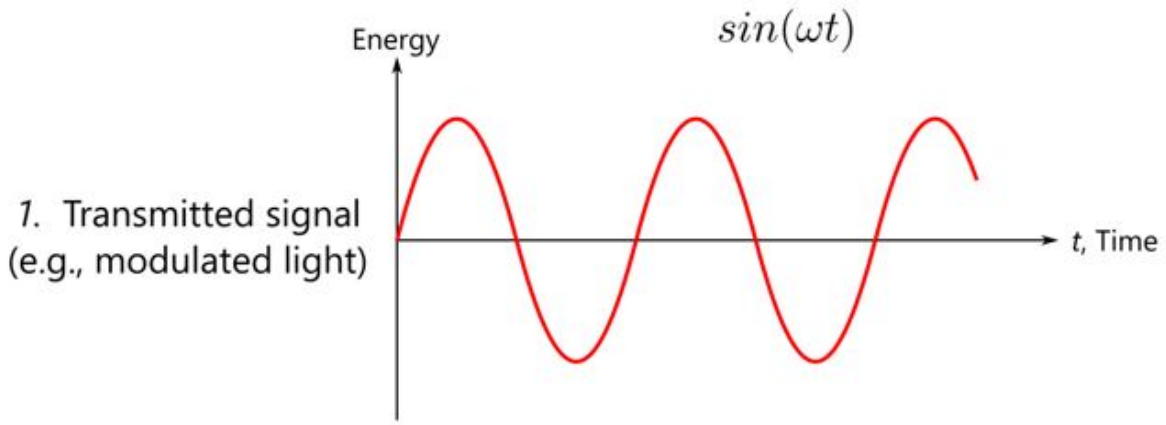

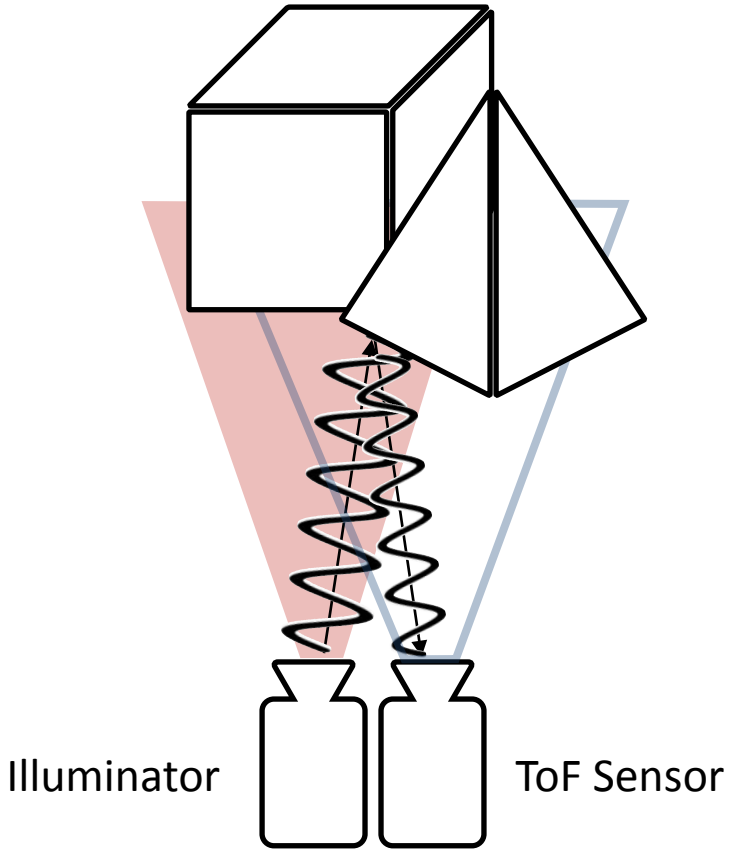

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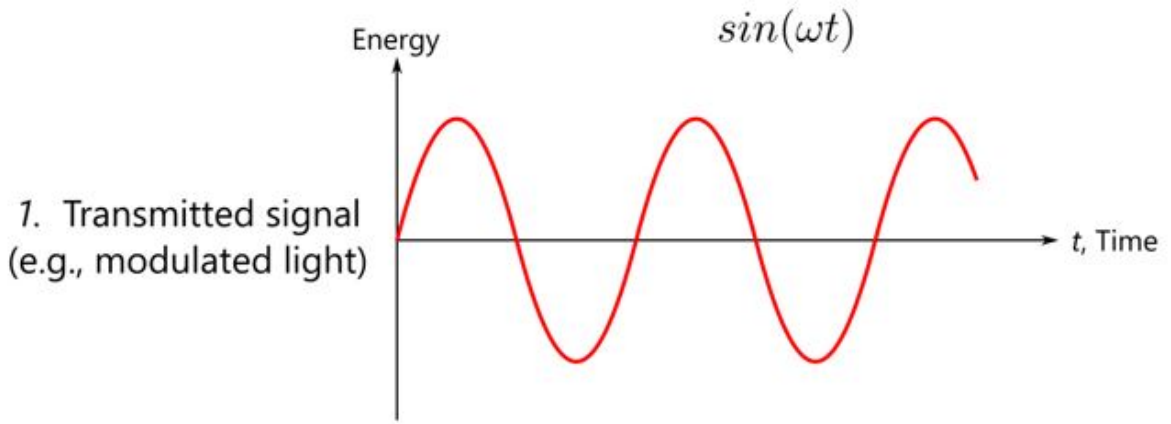

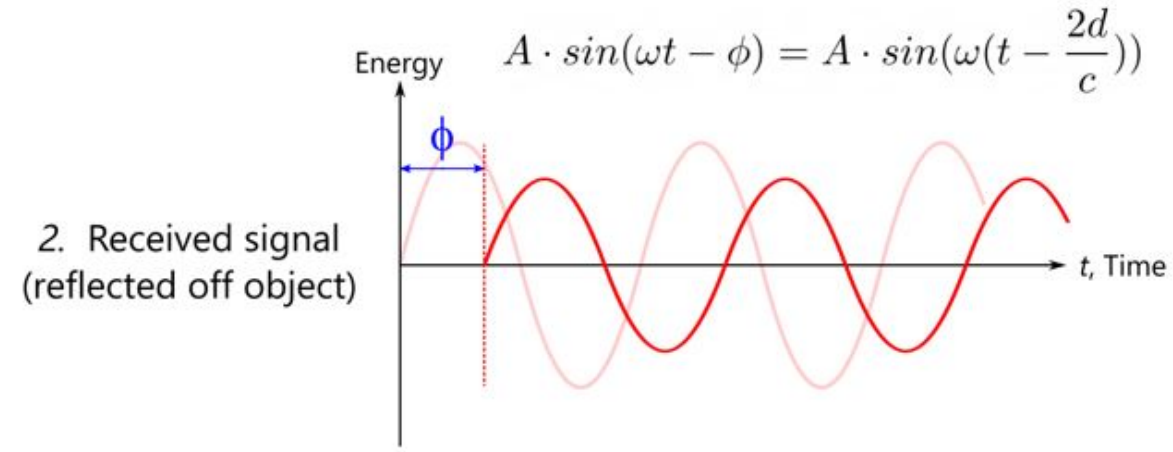

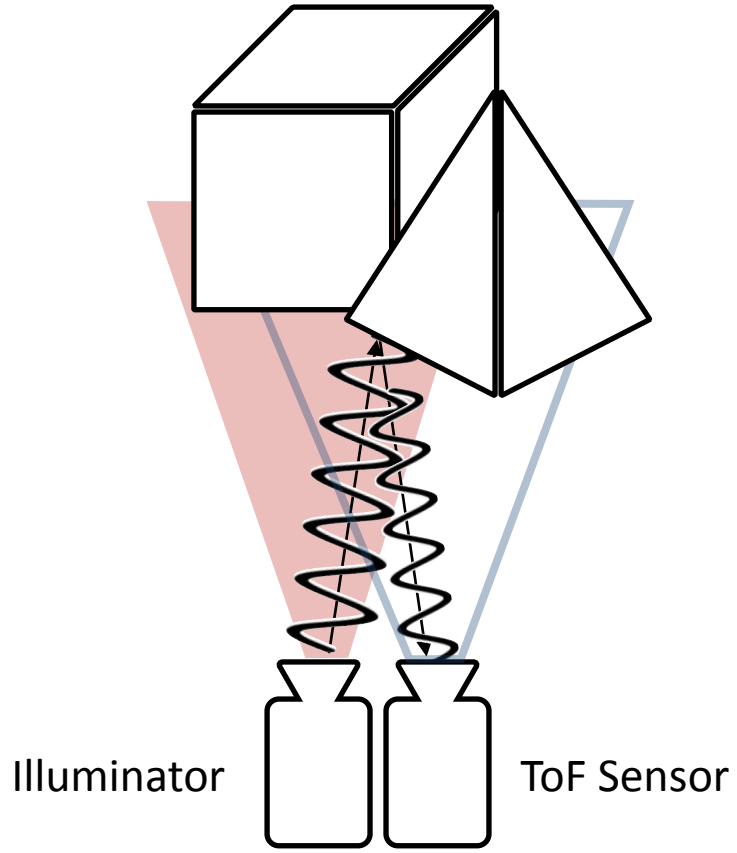

$$d = \frac{c \cdot \phi}{2 \cdot 2\pi f}$$

Distance to target · Speed of signal · Phase shift (in radians) · Round trip = 2 legs · Modulation frequency

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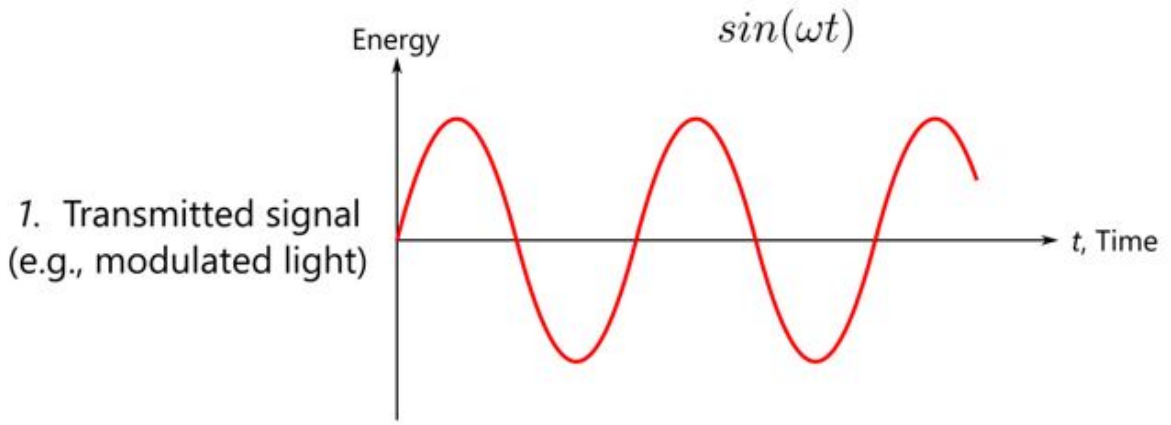

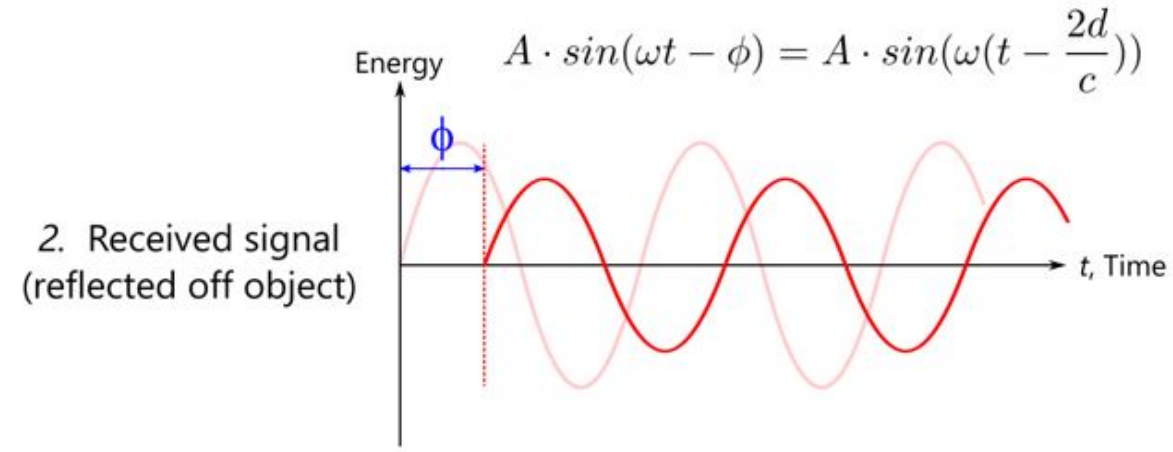

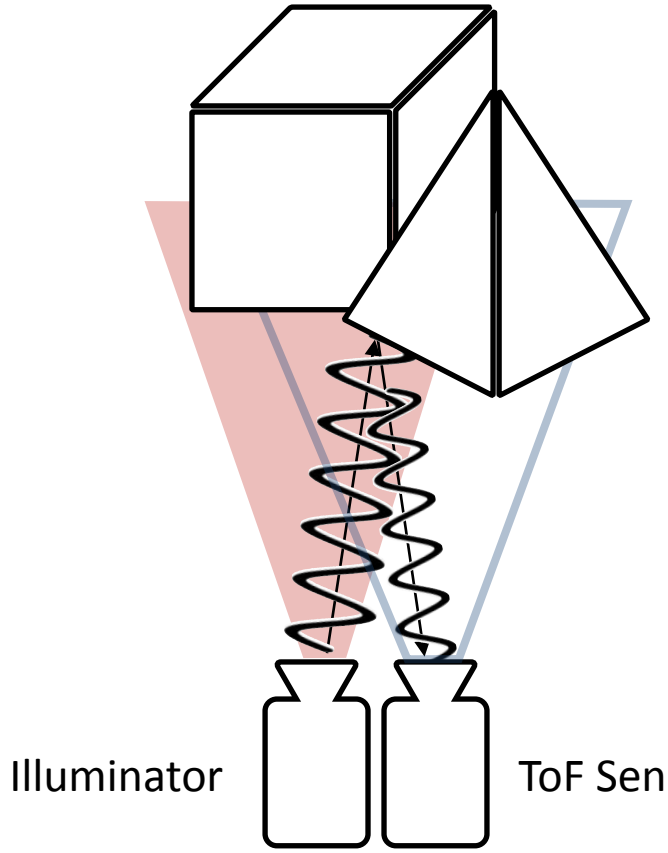

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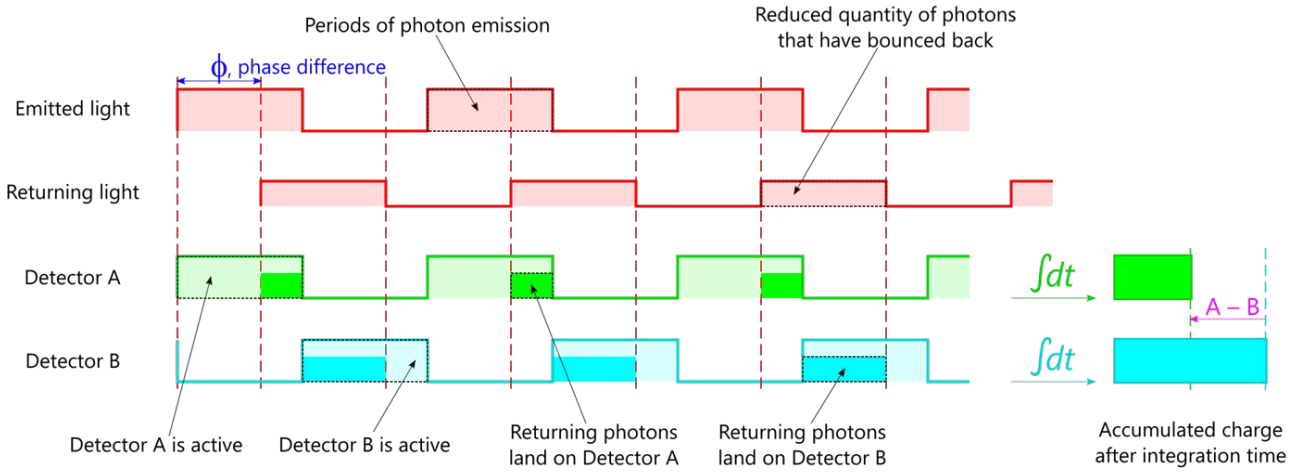
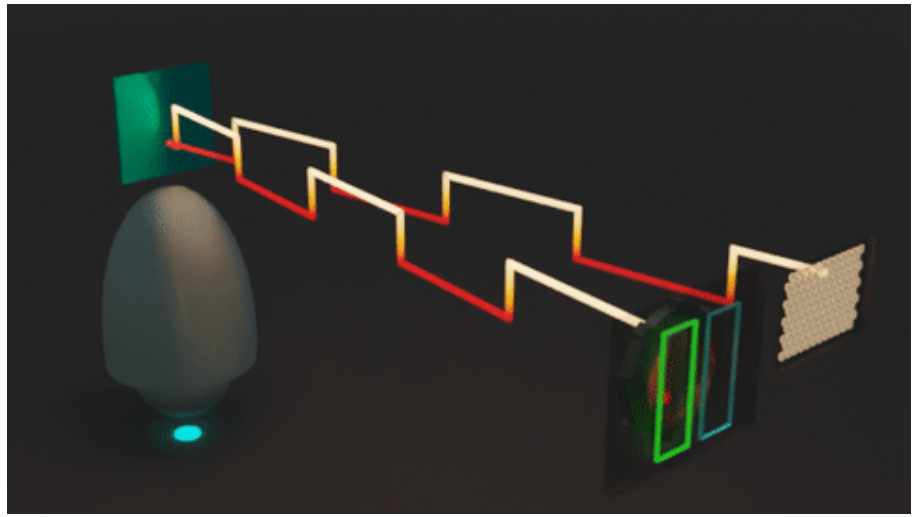
Distance to target; Speed of signal; Phase shift (in radians); Round trip = 2 legs; Modulation frequency

How to obtain?

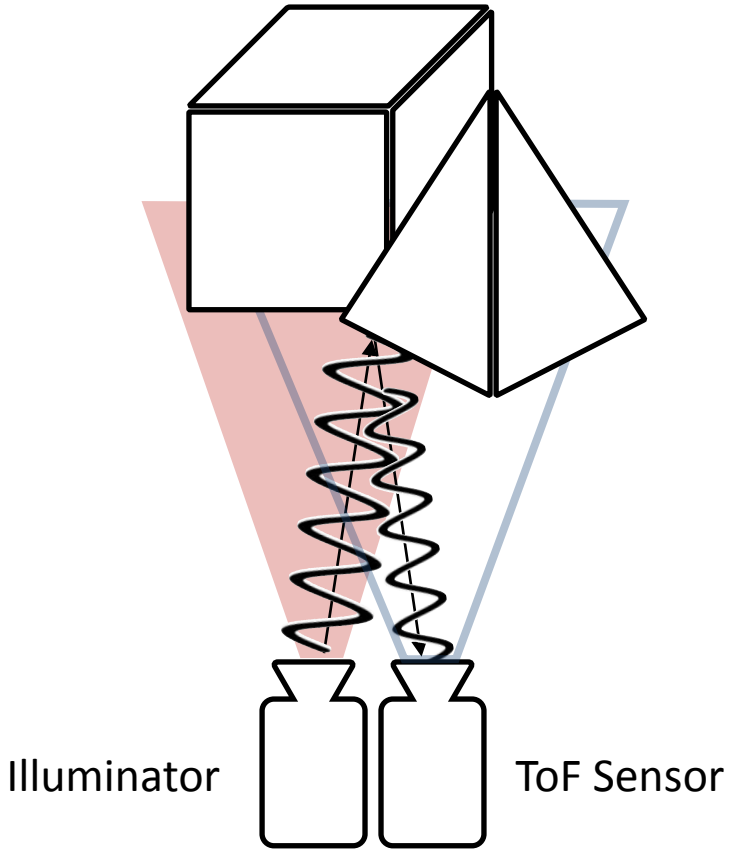
Indirect Time-of-Flight (ToF)

- Two detectors synchronised with the light emitter



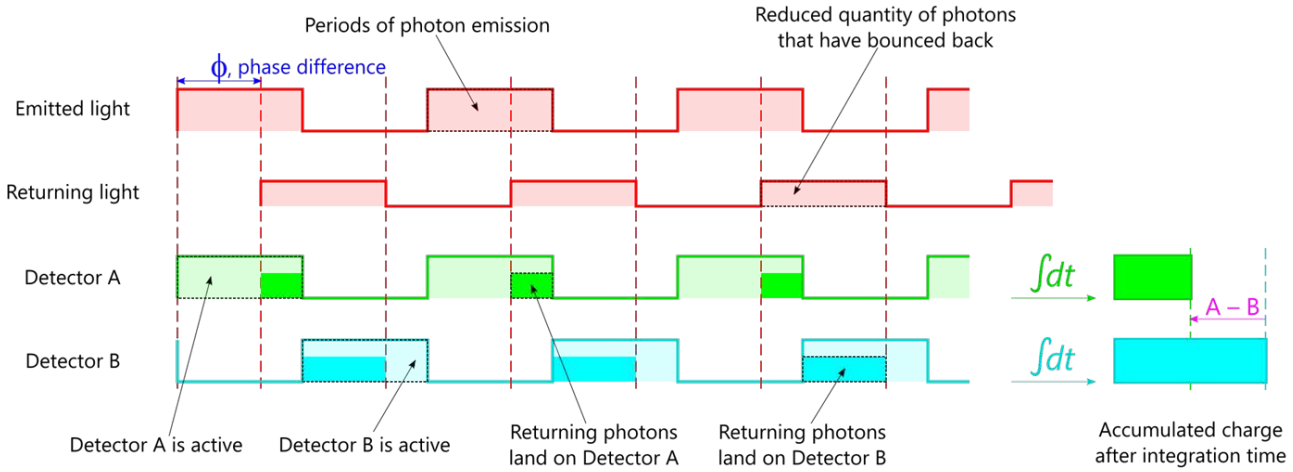


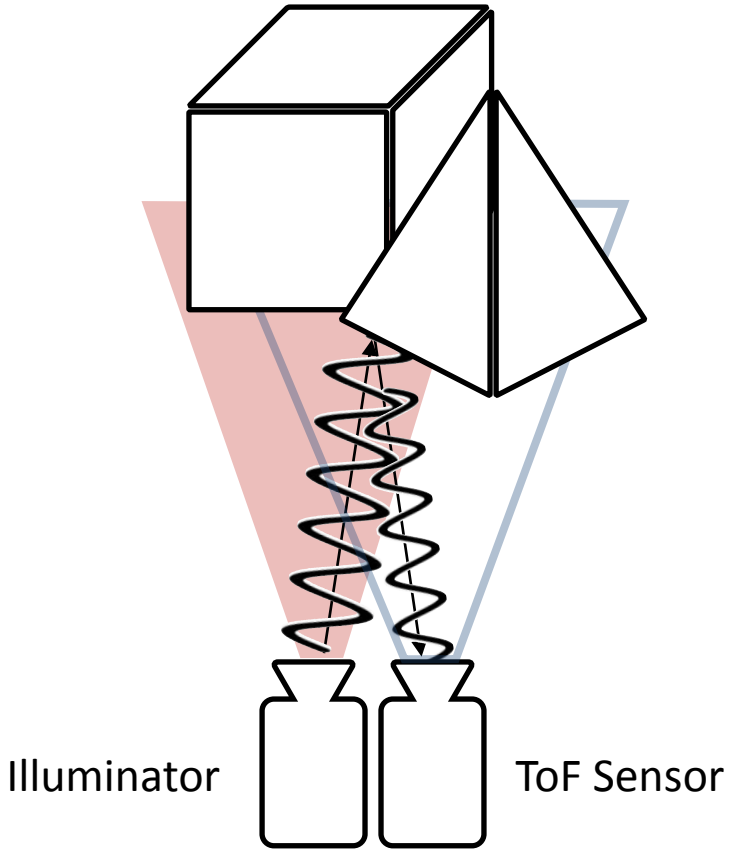
https://devblogs.microsoft.com



Indirect Time-of-Flight (ToF)

- Two detectors synchronised with the light emitter



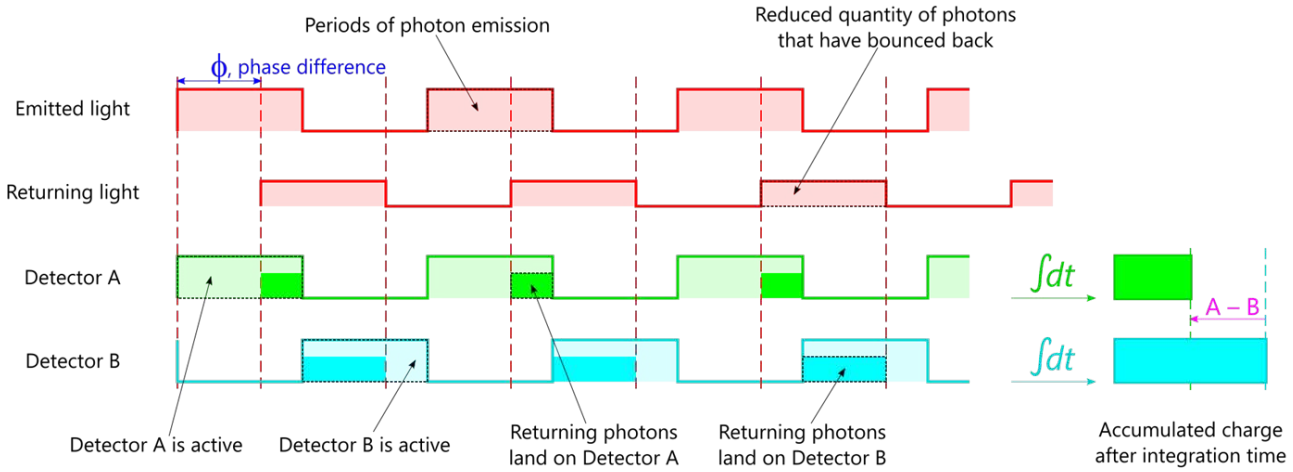


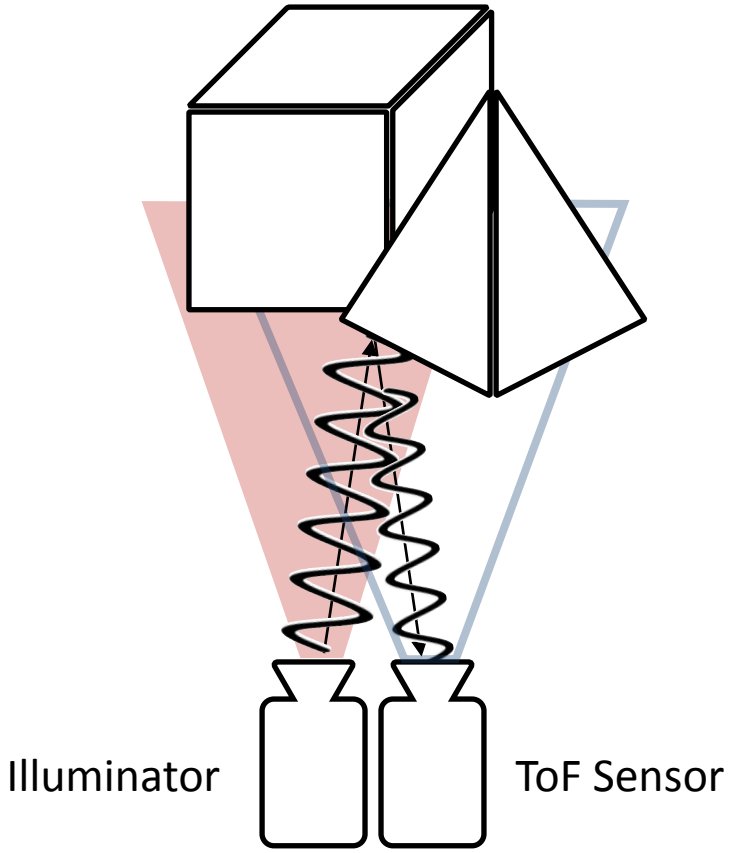
$$d = \frac{c \cdot \phi}{2 \cdot 2\pi f}$$

Distance to target: d
Speed of signal: c
Phase shift (in radians): ϕ
Round trip = 2 legs: 2
Modulation frequency: f

Indirect Time-of-Flight (ToF)

- Two detectors synchronised with the light emitter





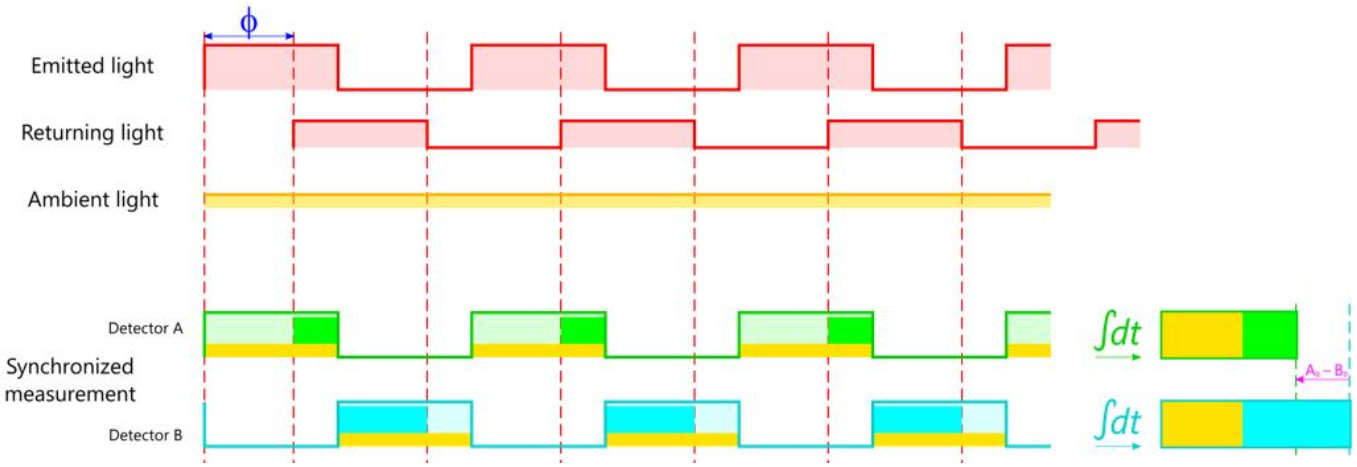
- What can go wrong?
  - Ambient light?
  - Ambiguity?

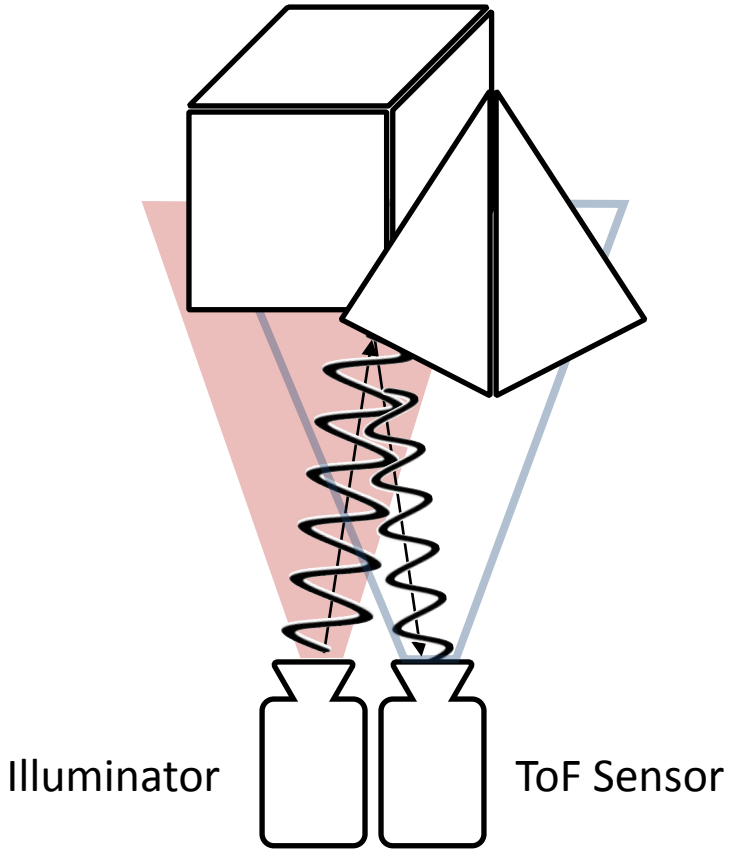
$$d = \frac{c \cdot \phi}{2 \cdot 2\pi f}$$

Distance to target; Speed of signal; Phase shift (in radians); Round trip = 2 legs; Modulation frequency

Indirect Time-of-Flight (ToF)

- Ambient light:
  - Usually not a problem





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Phase shift (in radians): ϕ
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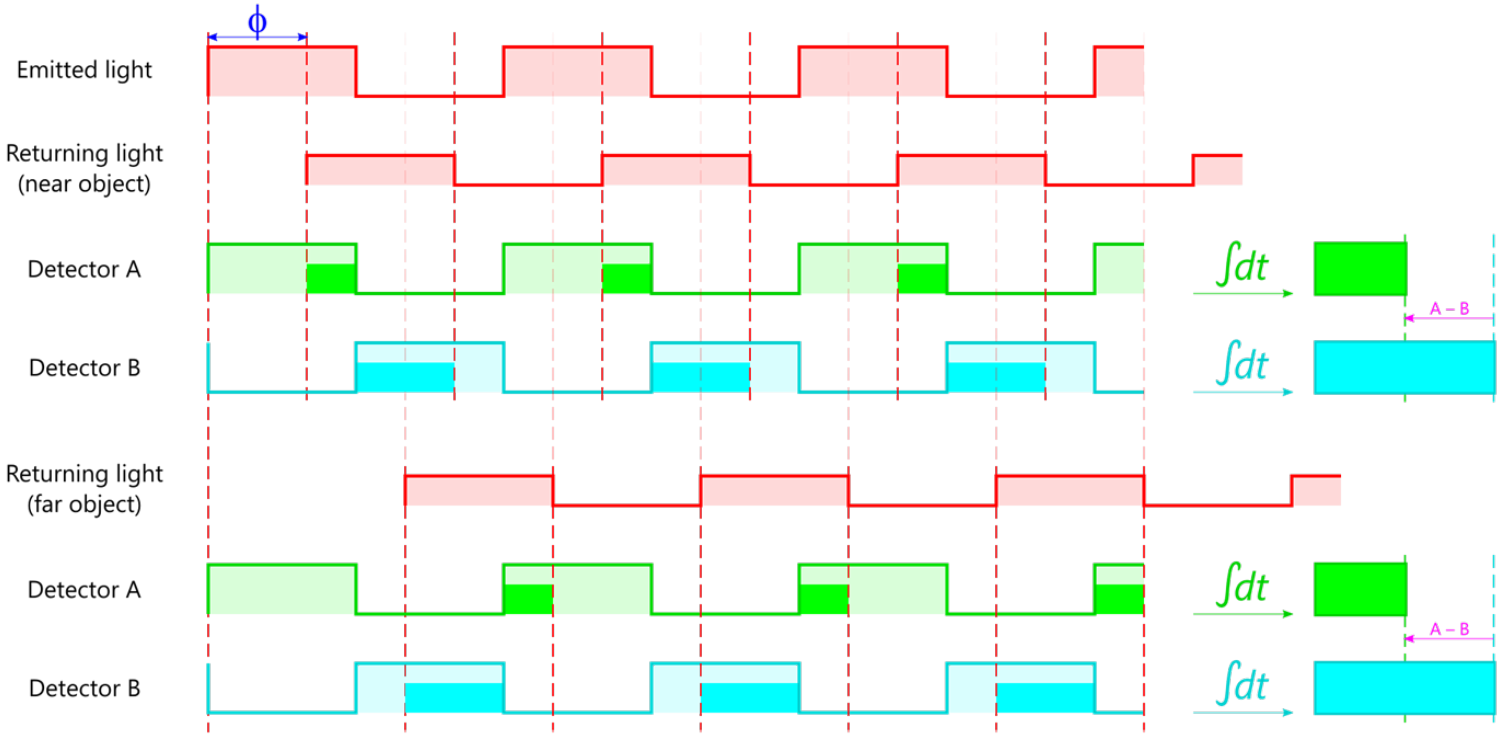
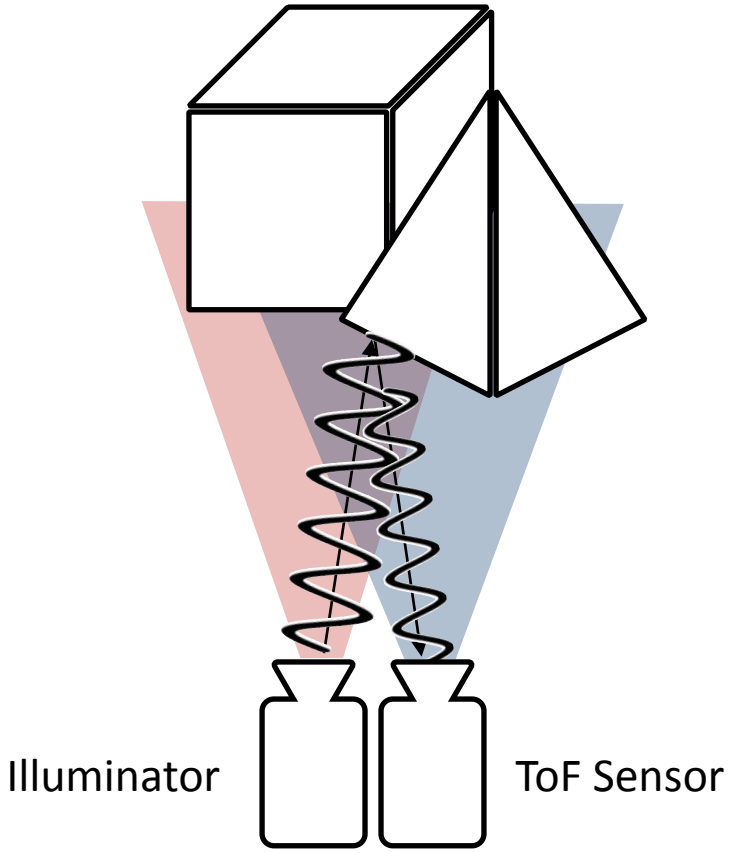
Indirect Time-of-Flight (ToF)

- Ambiguity
  - Usually a problem (e.g. object with another distance creating same phase measurement)





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Active range scanner / depth cameras work in infrared spectrum

We cannot perceive the infrared spectrum…

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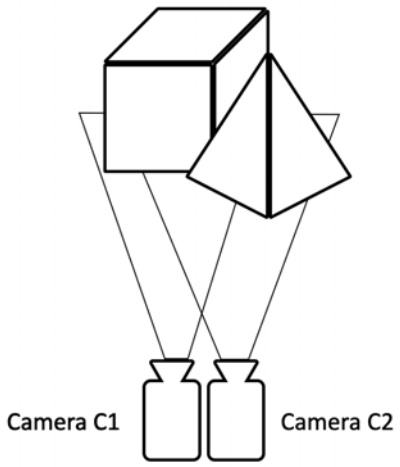
We cannot perceive the infrared spectrum…

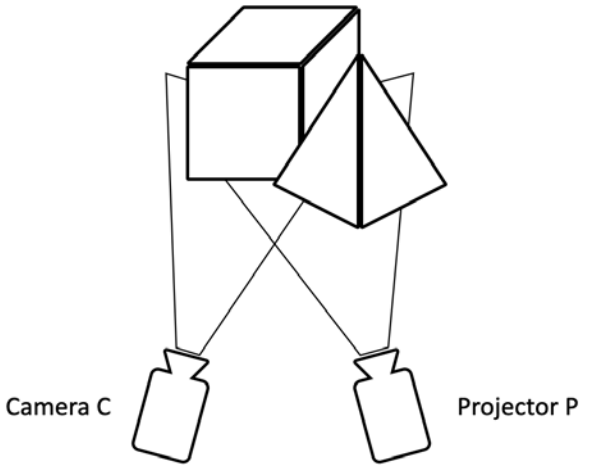


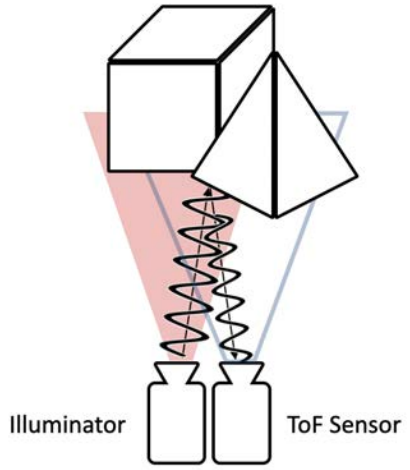
But they can…

Summary Range Scanning

Considerations	Stereo Vision (Passive)	Structured Light (Active)	Time of Flight (Active)
Response time / Speed			
Depth Accuracy			
Low light performance			
Bright light performance			

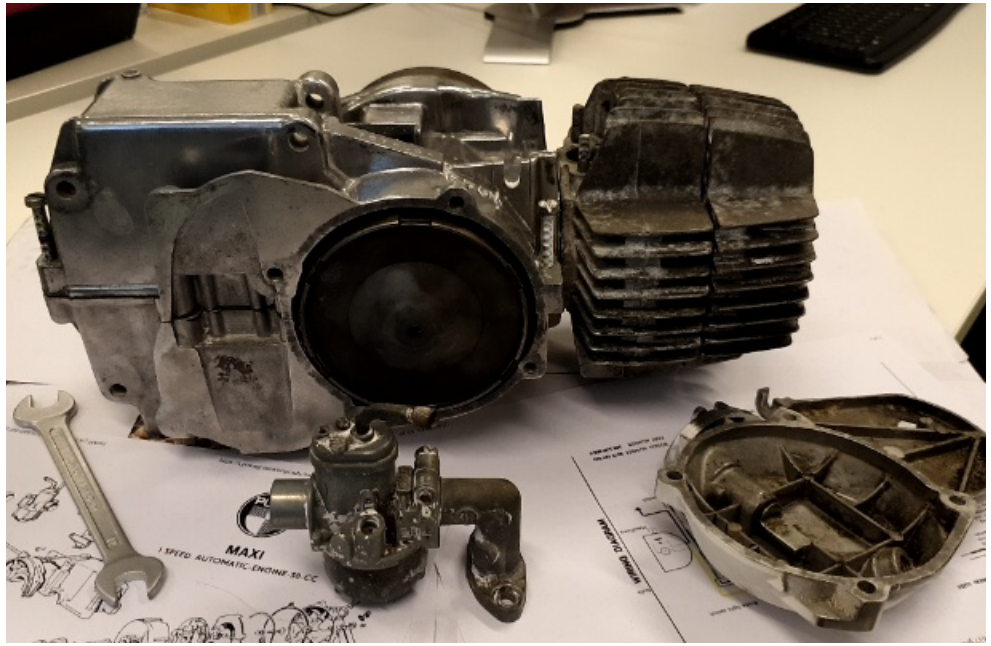


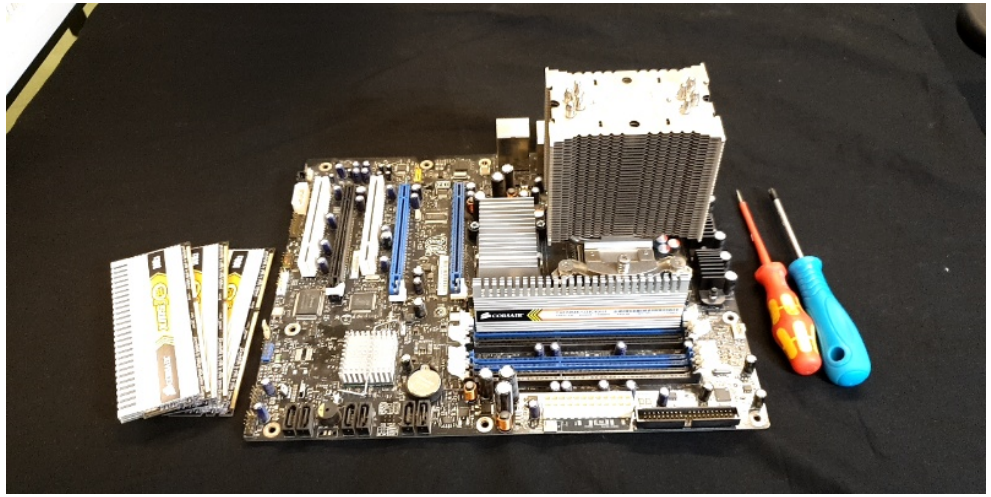


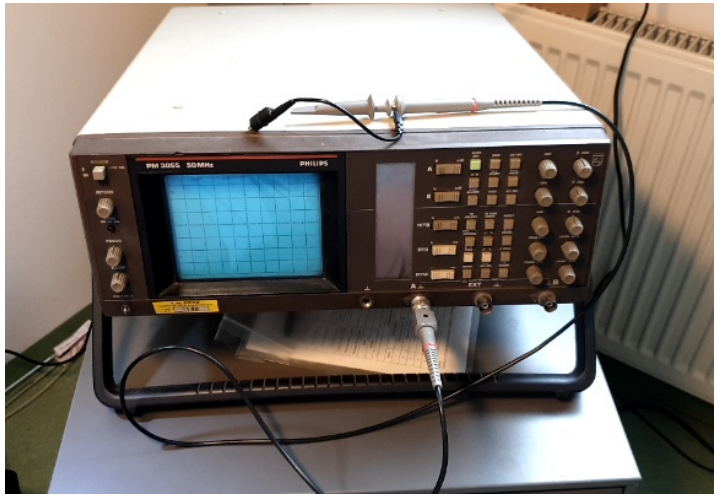


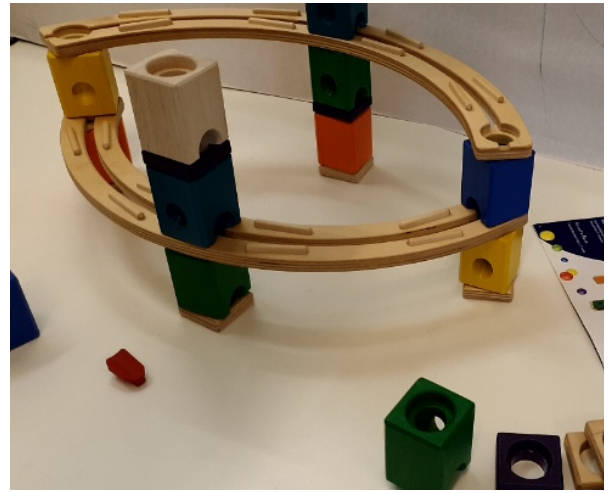
Summary Range Scanning

Any problems when scanning these objects?









No Depth Cam?

Depth from Mono / Depth Estimation using ML

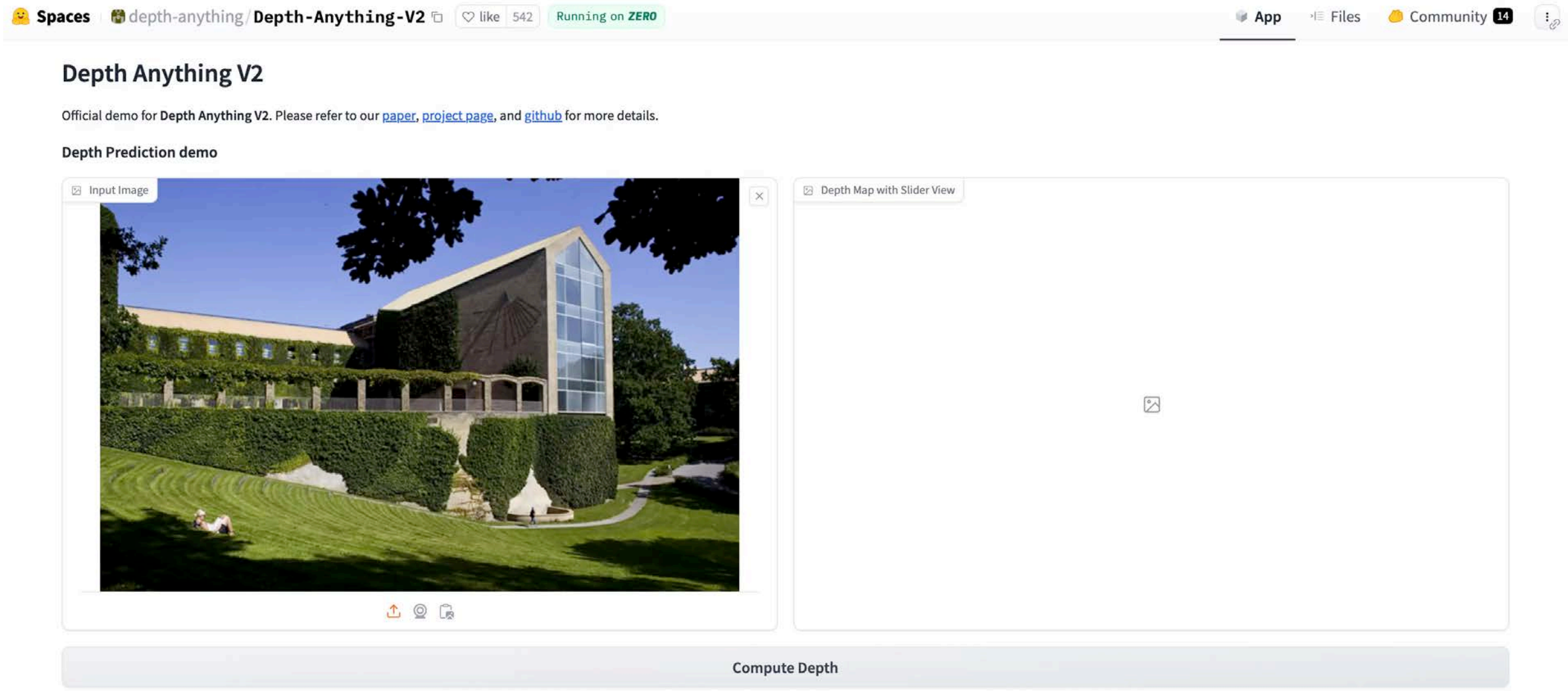
- Convolutional neural networks (CNNs) have been applied to monocular depth estimation
- Common architectures include U-Net, ResNet, and DenseNet
- During training:
  - Network is given pairs of images and their corresponding ground-truth depth maps
  - Minimize the difference between predicted depth and ground truth depth

https://github.com/yuhsuanyeh/BiFuse

Depth from Mono: Depth Anything V2

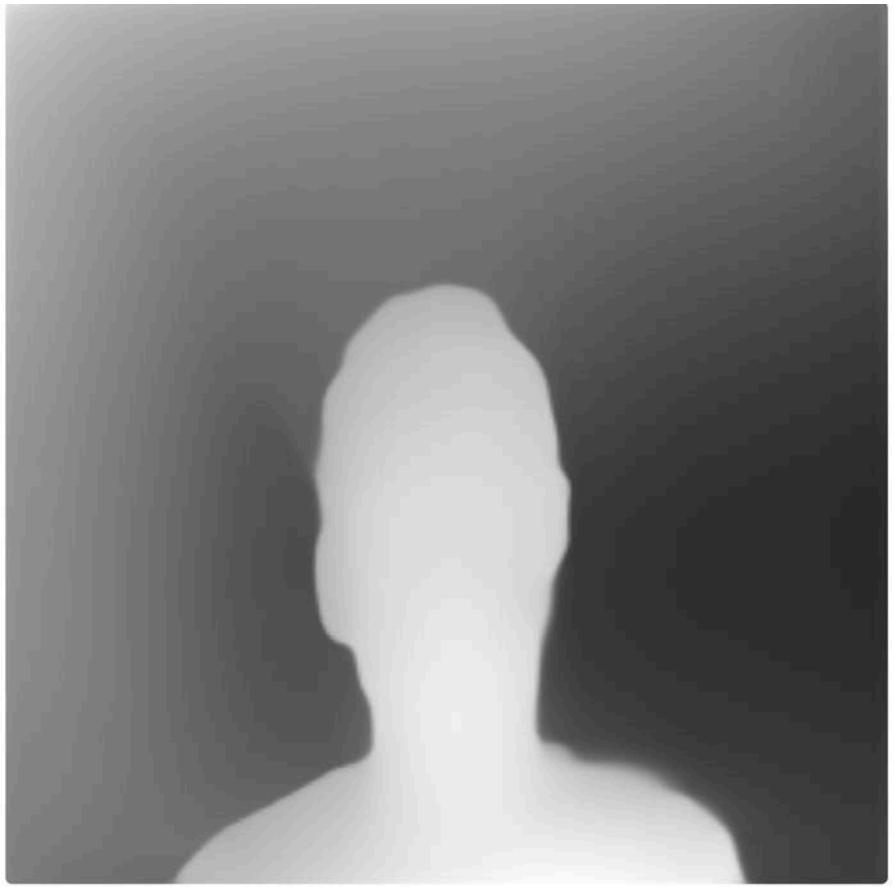
https://huggingface.co/spaces/depth-anything/Depth-Anything-V2

Depth from Mono: Depth Anything V2



https://huggingface.co/spaces/depth-anything/Depth-Anything-V2

Depth from Mono: Tensorflow JS



Average Depth: 126.56

https://kuromadara.github.io/live-depth-prediction-using-tfjs/

Reminder: Depth from Mono / Depth Estimation using ML

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- Common architectures include U-Net, ResNet, and DenseNet
- During training:
  - Network is given pairs of images and their corresponding ground-truth depth maps
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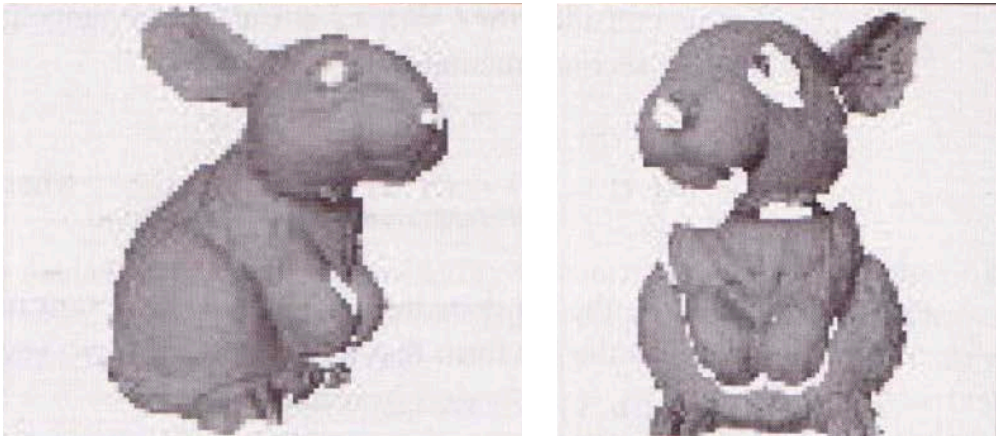
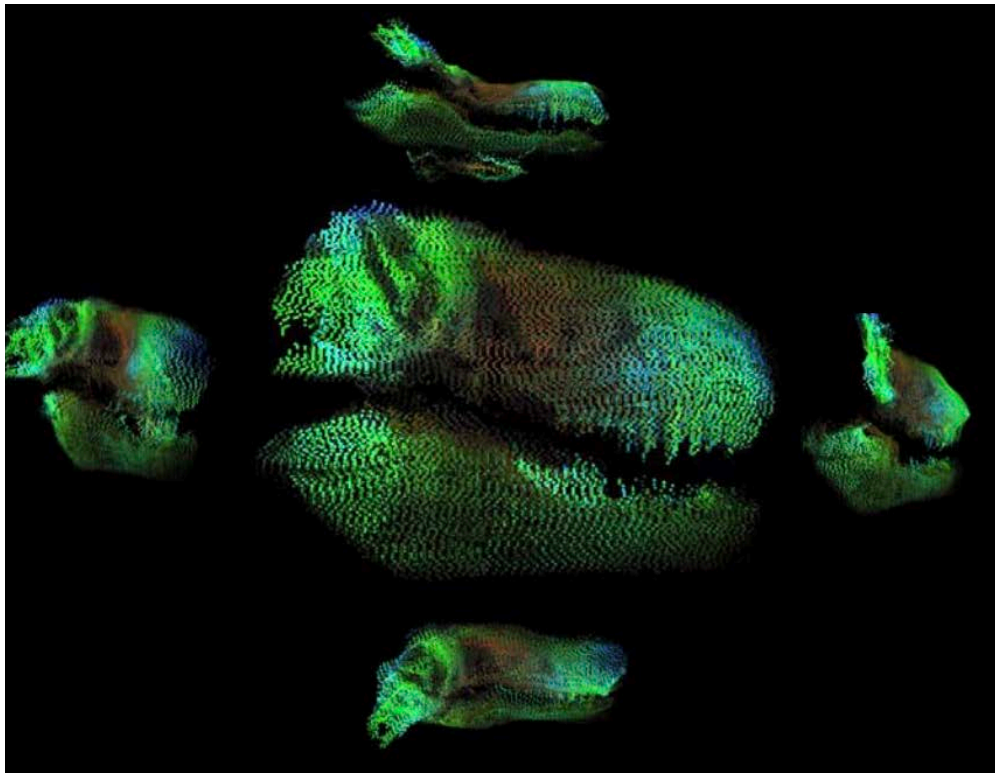
Registration of Depth Maps

Registration of Depth Maps

- If correspondences are known, the depth (distance from camera / projector to scene point) can be estimated for every pixel (depth map)
- Having multiple depth maps of the same scene, how can they be merged?
- This process is known as registration





Iterative Closest-Point Method

- Registration of two sets of three-dimensional points requires the computation of a rigid transformation that maps the first point set (B) to the second one (A)
- Iteratively minimise the average distance between the two point sets:
  - Find correspondences between the sets by matching every point in B with the point closest to it in A
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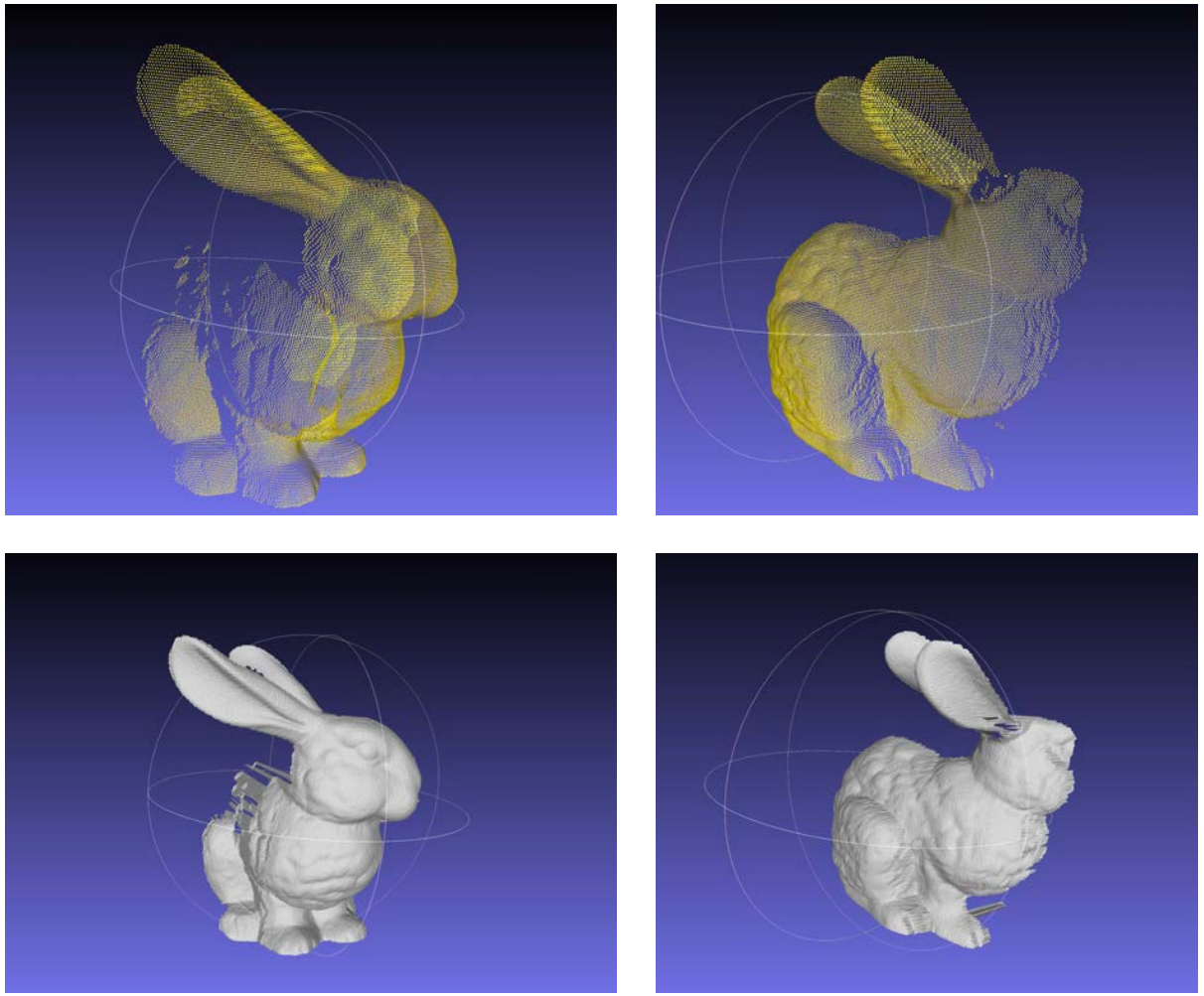

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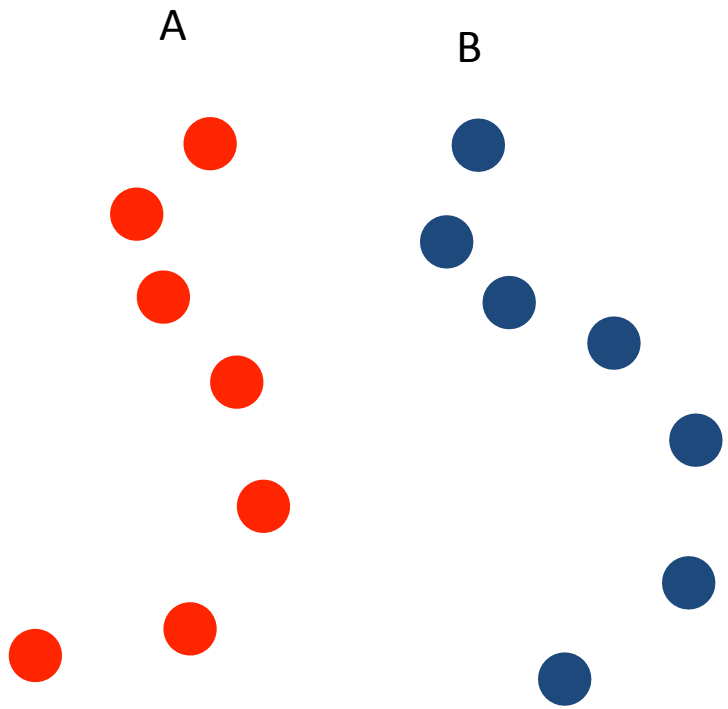

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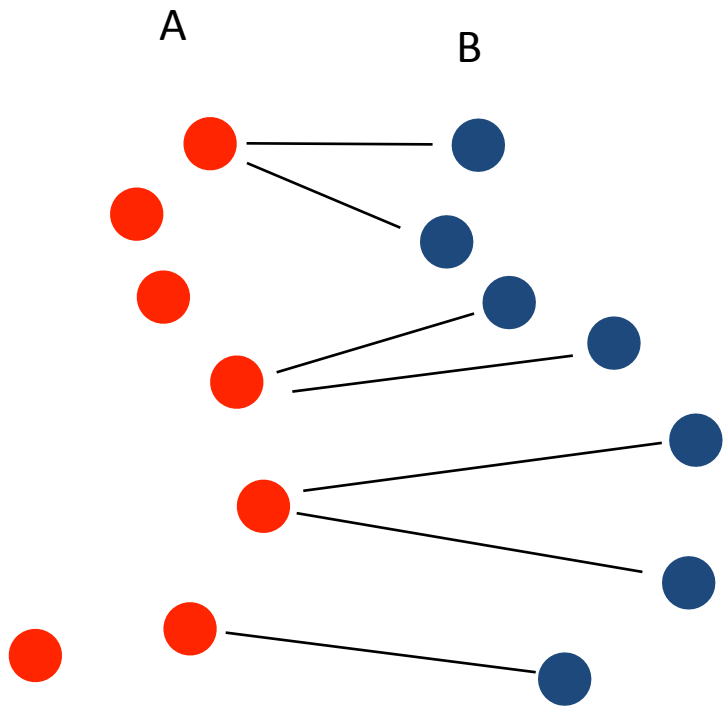

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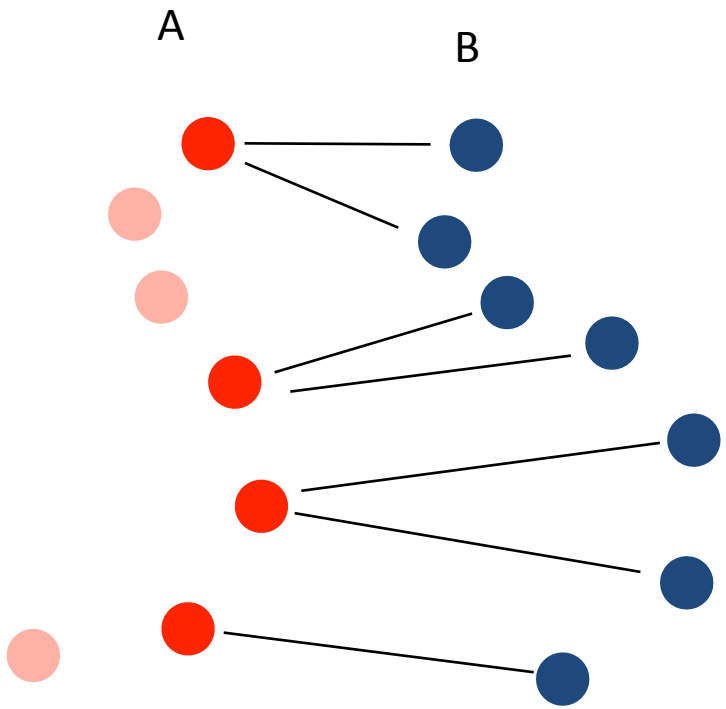

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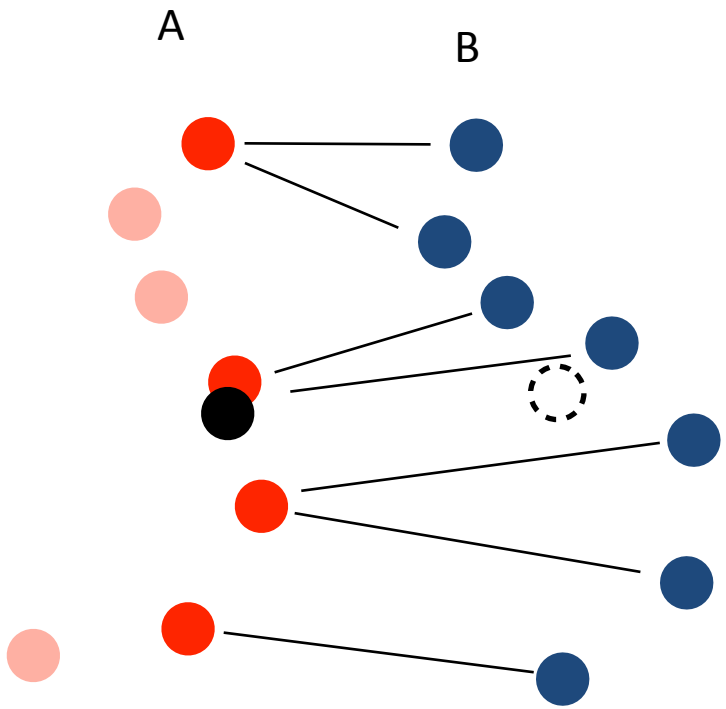

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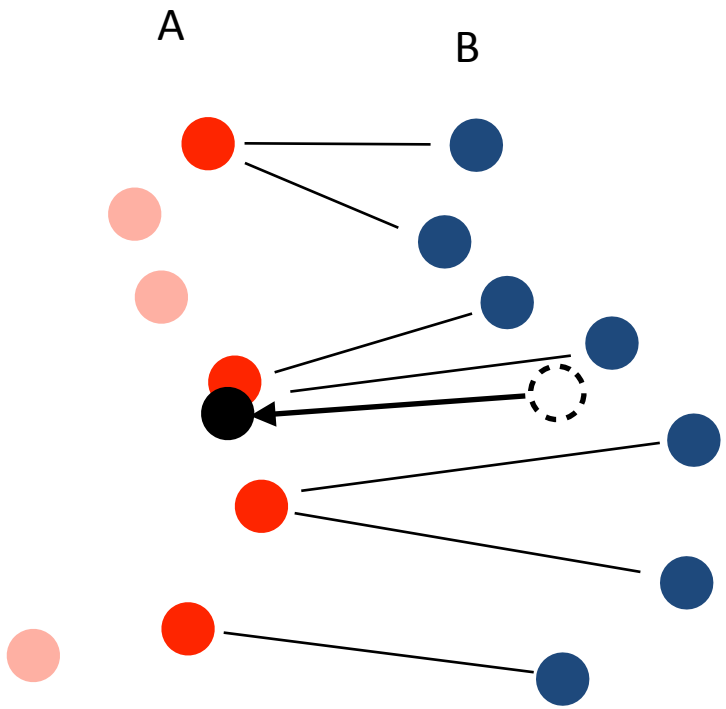

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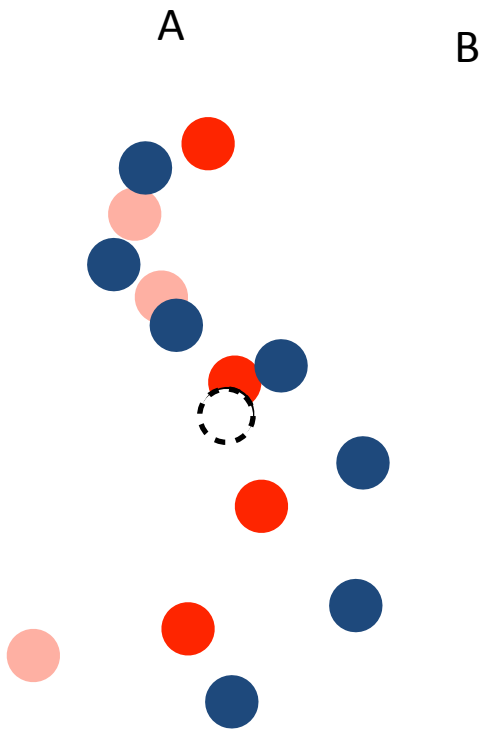

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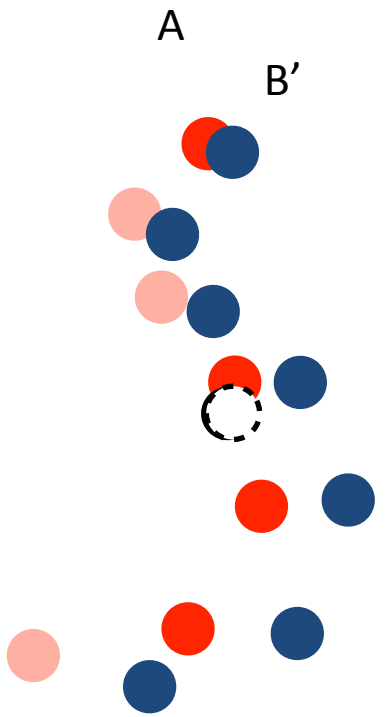

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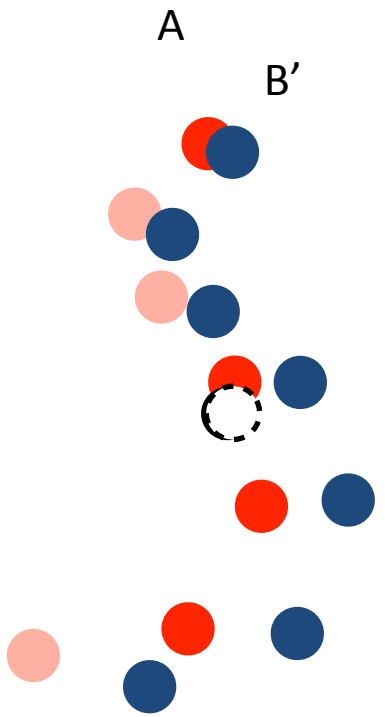

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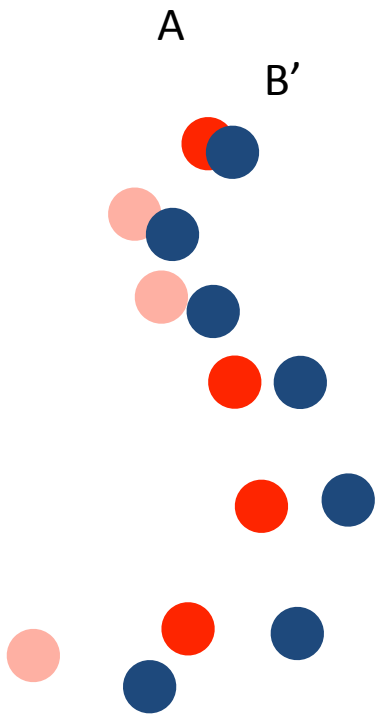

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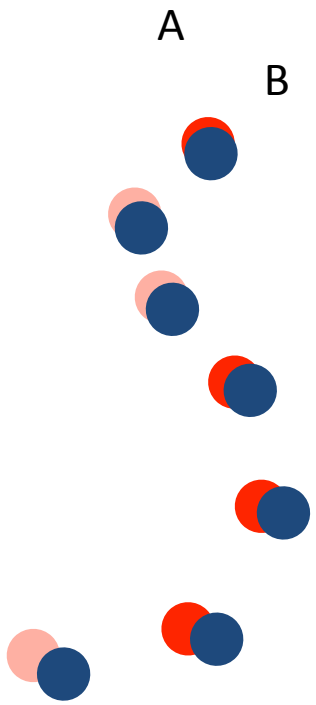

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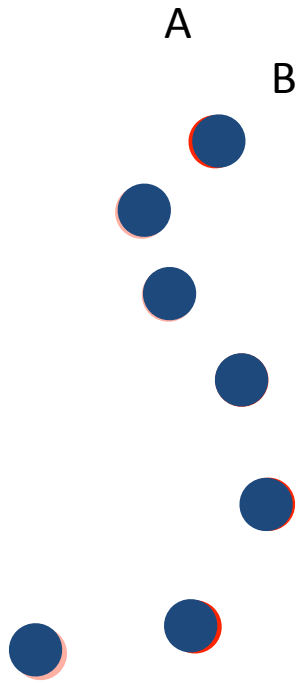

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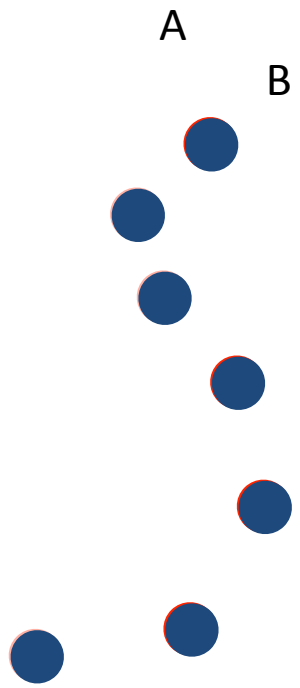

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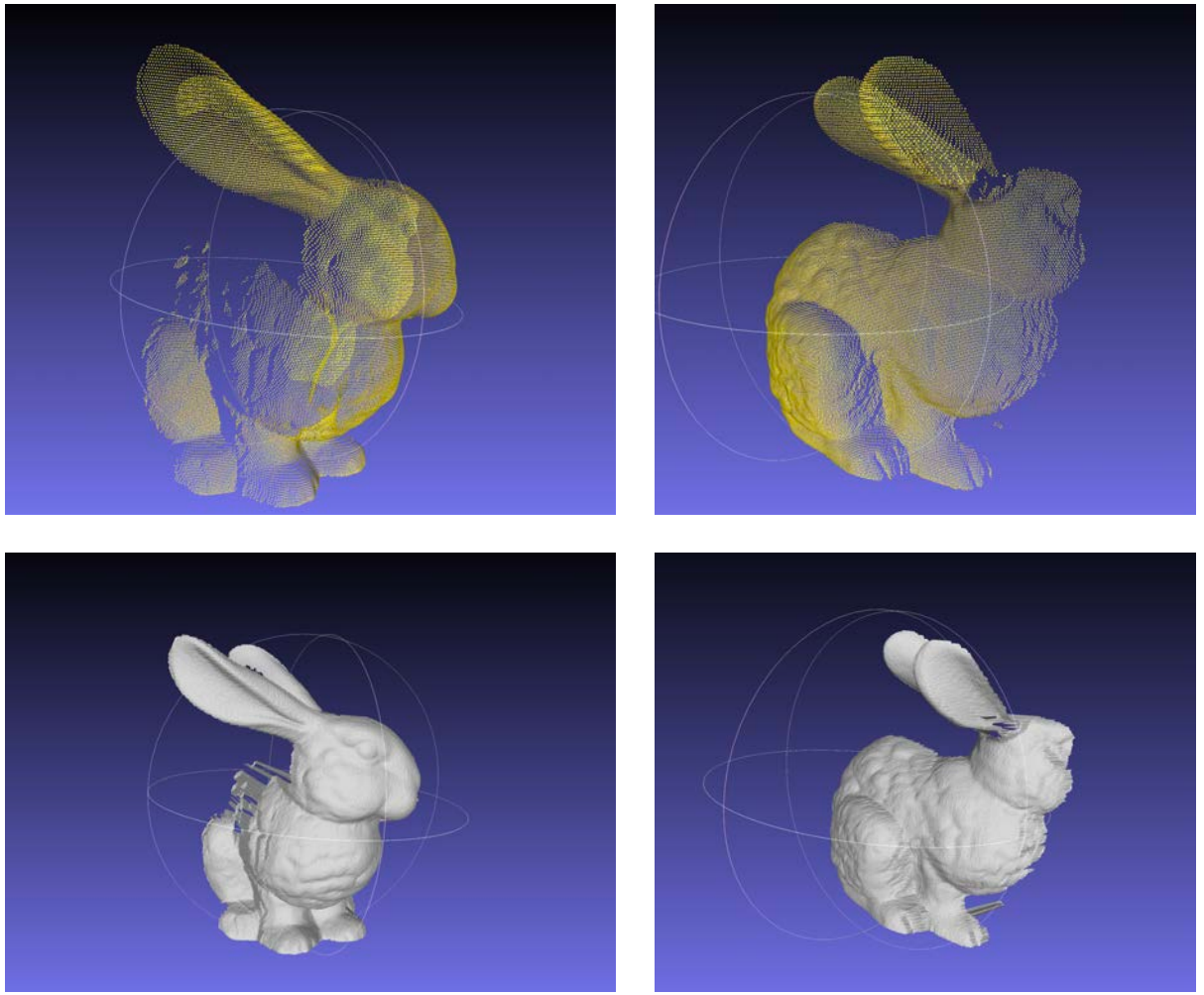

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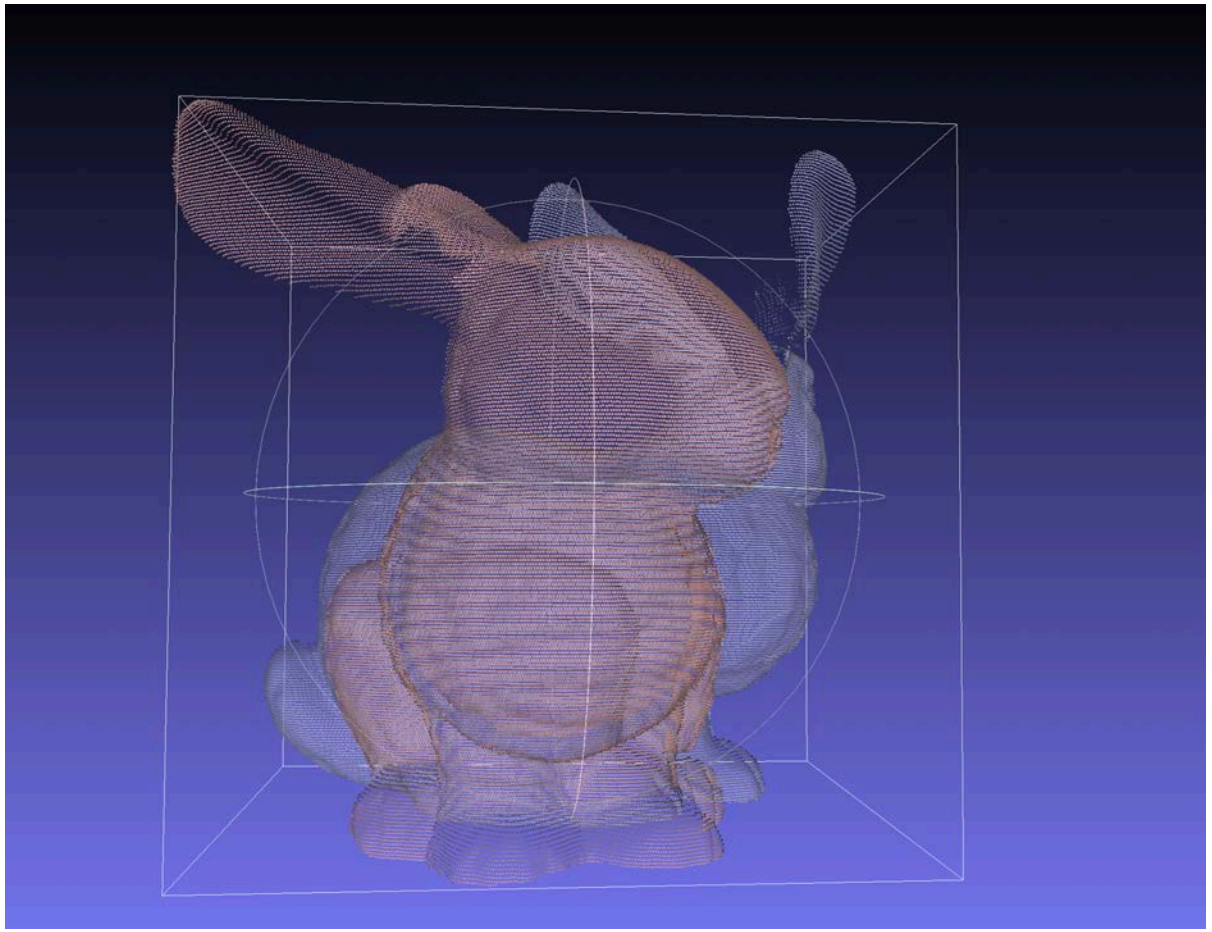

ICP in Meshlab

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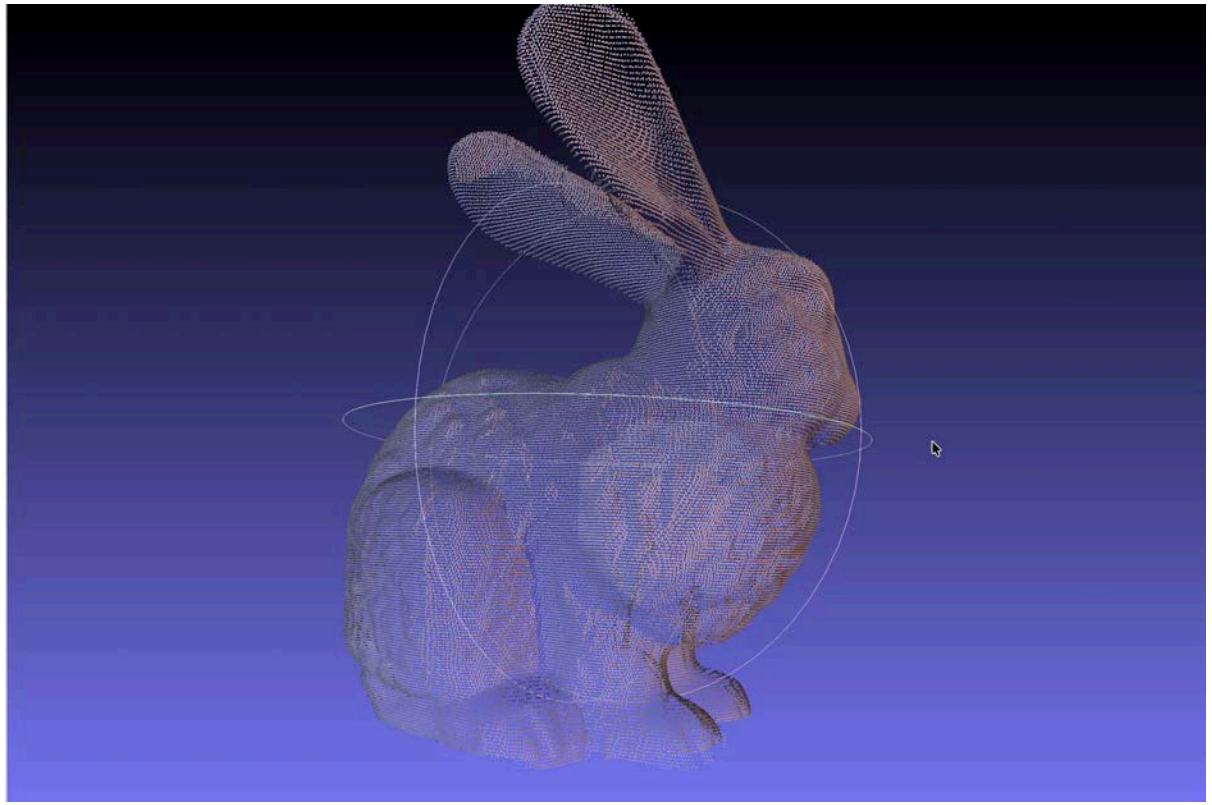
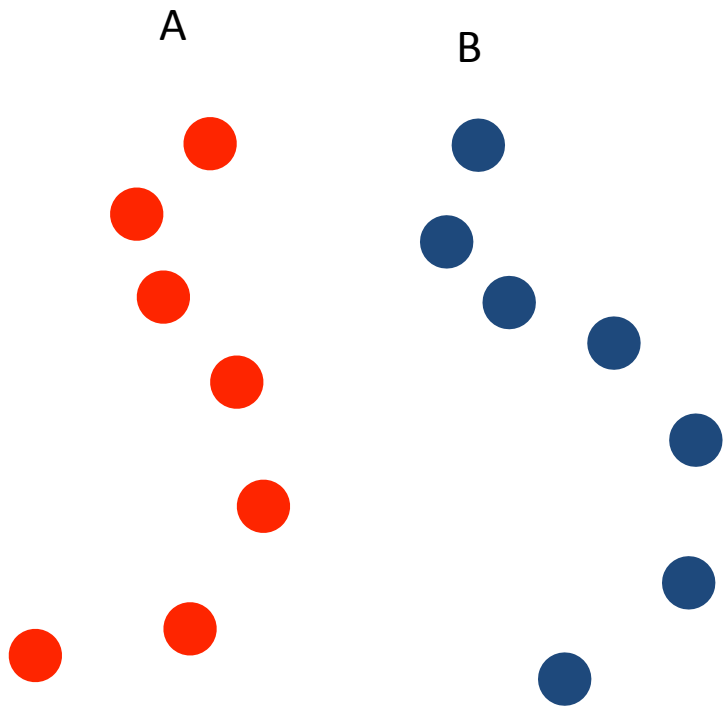


ICP in Meshlab

Iterative Closest-Point Method

- How to find a reasonable initial guess?



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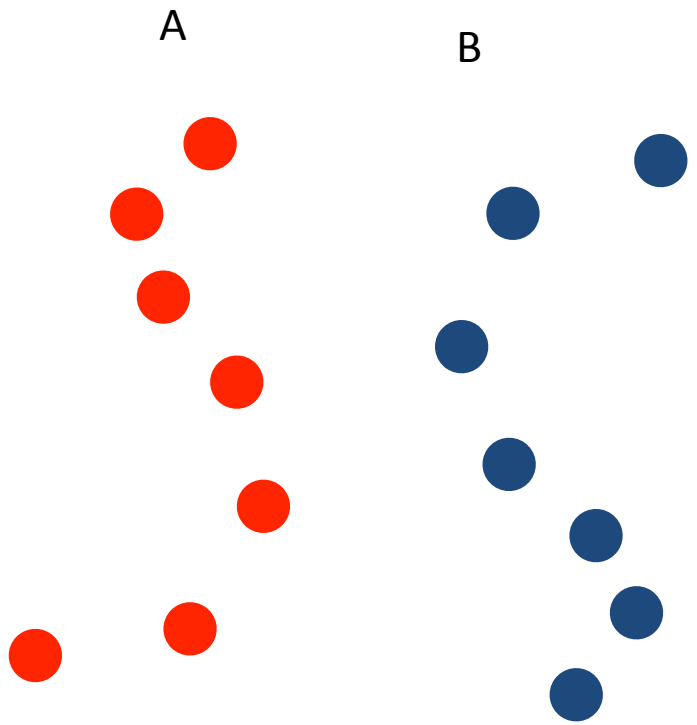
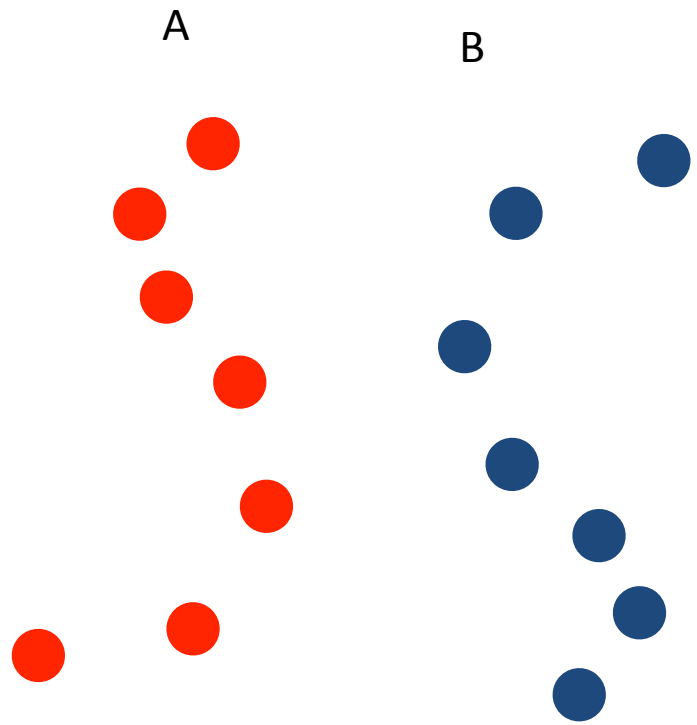


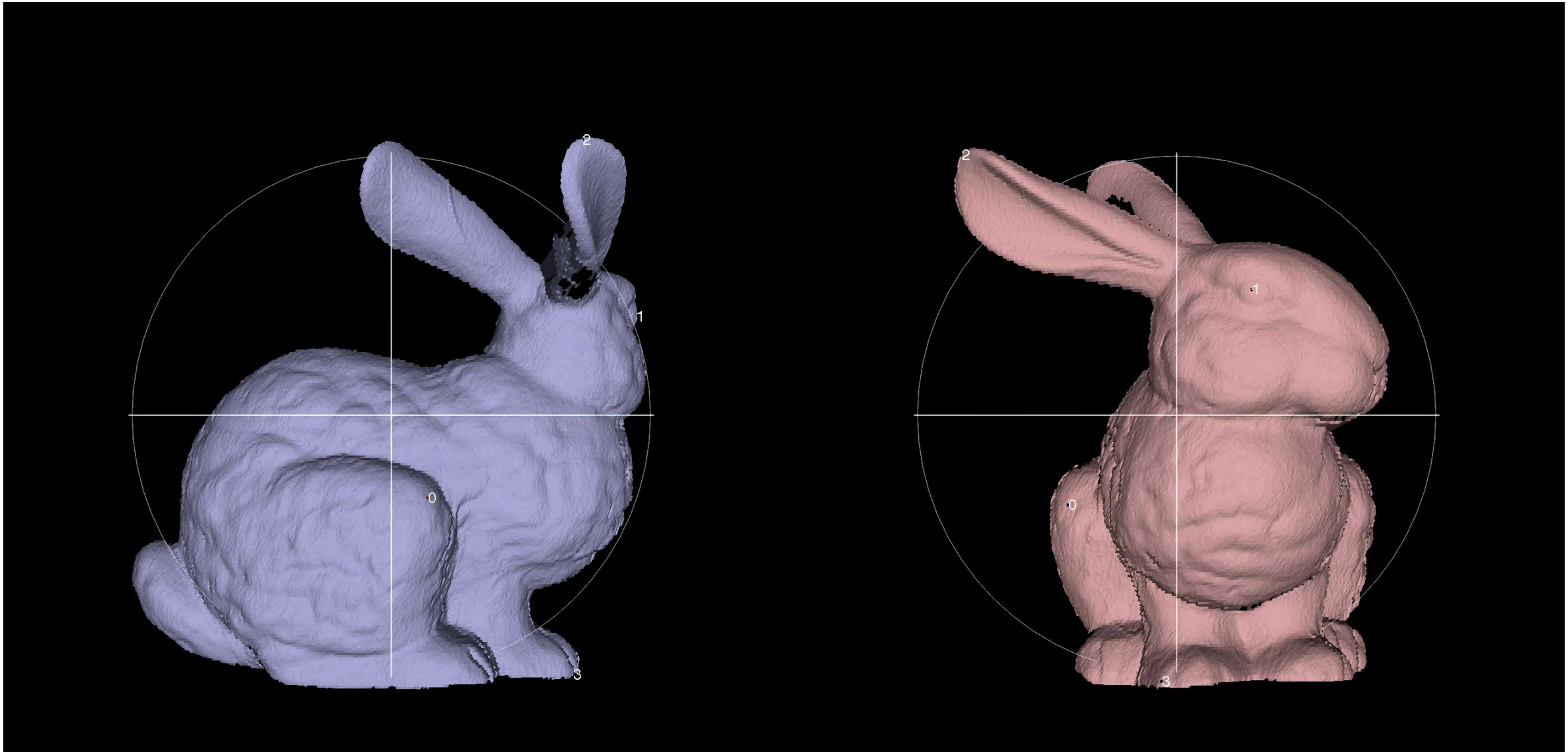
Iterative Closest-Point Method

- How to find a reasonable initial guess?
  - Manually
  - Matching distinctive features between clouds
  - Using sensor data
  - Global registration algorithms (algorithms not needing initial guess)

- At every iteration finding the closest point M in A to a given point S in B takes (for n points) how long?
  - O(n2) brute-force
- Can this be done faster?
  - O(log n) for nearest-neighbour matches with k-d trees



Iterative Closest-Point Method



Manual alignment in Meshlab to initialise ICP

Iterative Closest-Point Method

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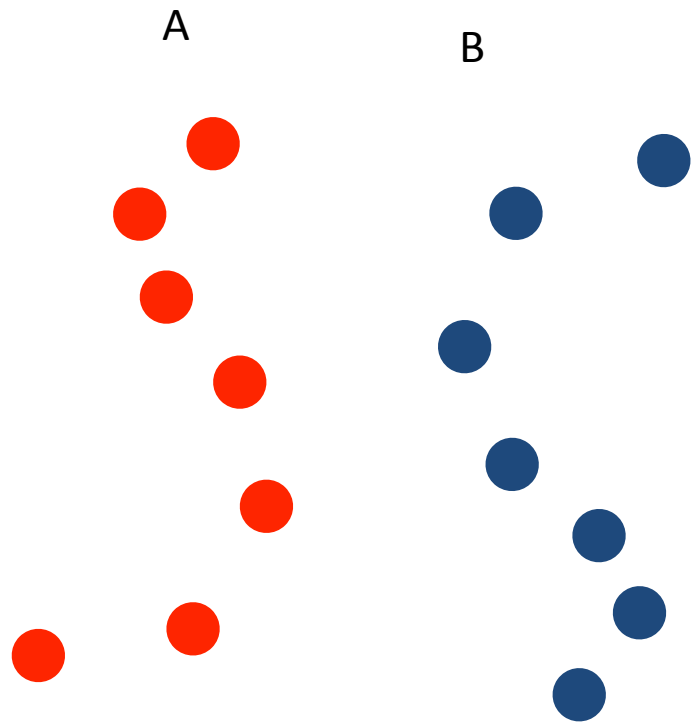
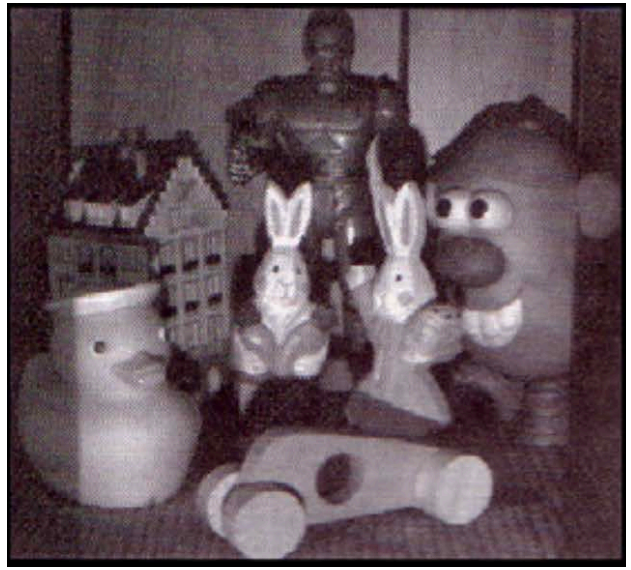
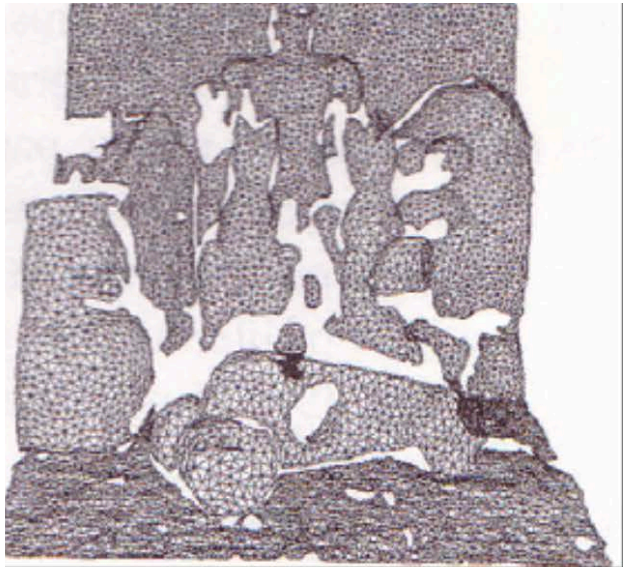


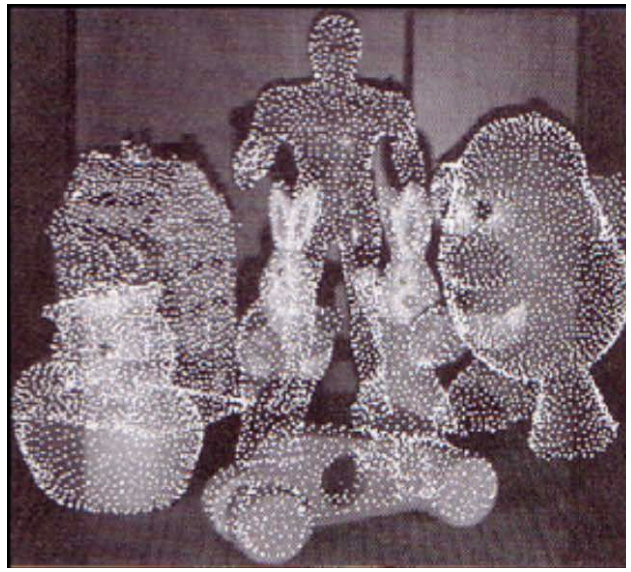
Processing Depth Maps

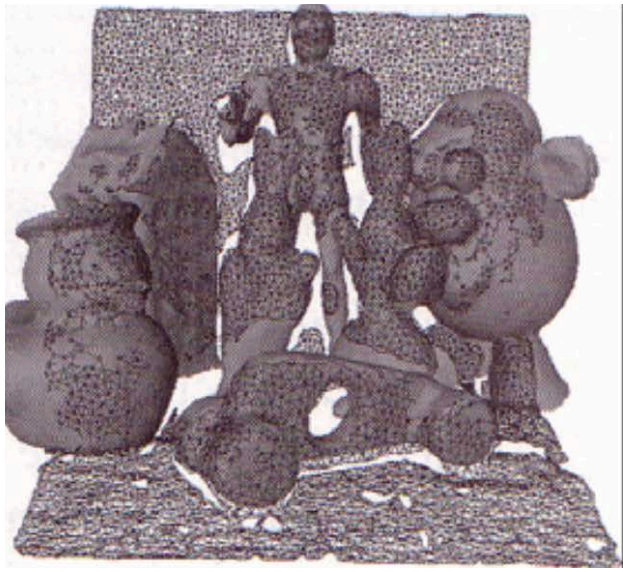
Processing Depth Maps

- Depth maps can be processed like images
- Image operators, such as filters, can be applied to:
  - Handle discontinuities and overlaps
  - Fill missing portions
  - Smoothen geometric noise
  - Analyse depth images
    - Find features such as edges
    - Segmentation of objects
    - Etc.









The end!