Introduction to Light-Field Imaging I

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Introduction to Light-Field Imaging

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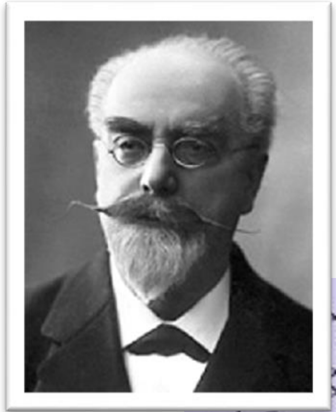
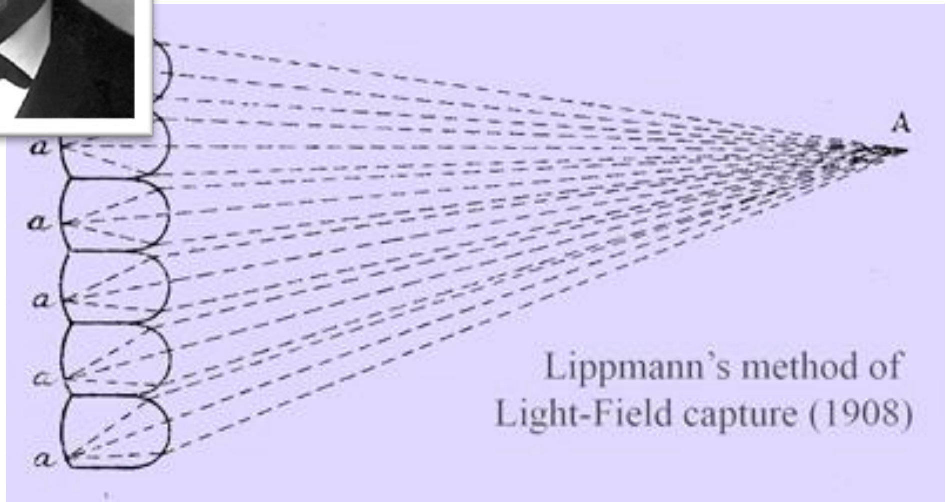
   d) 3D Volumetric Velocimetry
   e) and more…

Introduction





Lippmann's method of
Light-Field capture (1908)

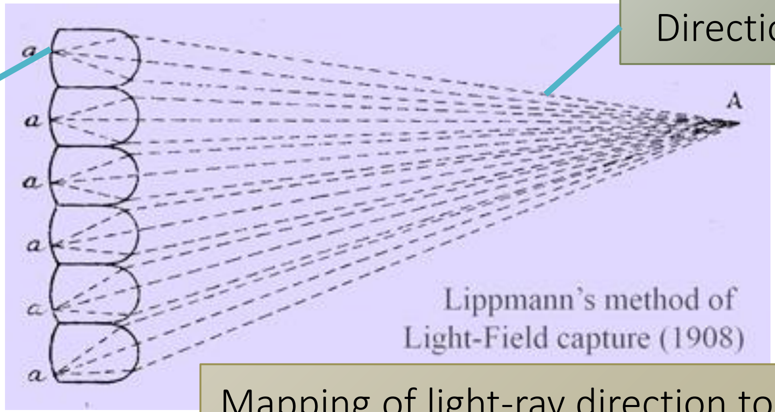
Some History

- 1903 Ives (barrier camera)
- 1908 Lippman (microlens camera)
- 1911 Sokolov
- 1935 Coffey
- 1948 Ivanov
- 1968 Chutjian (first digital lightfield device)
- 1970 Dudnikov
- 1991 Adelson (plenoptic camera)
- 1996 Levoy & Hanrahan (lightfield)
- 2000 Isaksen (refocusing)
- 2005 Ng (handheld plenoptic camera)
- 2006 Levoy (microscopy)
- 2006 Georgiev & Lumsdaine (plenoptics 2.0)
- 2008 Fife (plenoptic CCD sensor)
- 2010 Raytrix (first commercial lightfield camera)
- 2011 Lytro (first consumer lightfield camera)

First Described Light-Field Capturing Device (1908)

Position

Direction



Mapping of light-ray direction to position.

Lippmann
(Nobel prize for
color photography)

Deriving the lens curvature equation
for a section of Lippmann's film
"Light-Field film"

$$\frac{\sin\alpha}{\sin\beta} = n$$

$$\delta = \alpha - \beta = \alpha(1 - \frac{1}{n}) = \alpha\frac{n-1}{n}$$

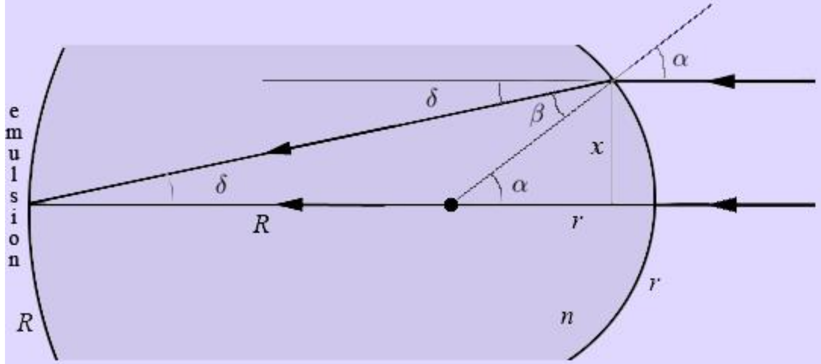
$$(R+r)\delta = x$$

$$(R+r)\frac{x}{r}\frac{n-1}{n} = x$$

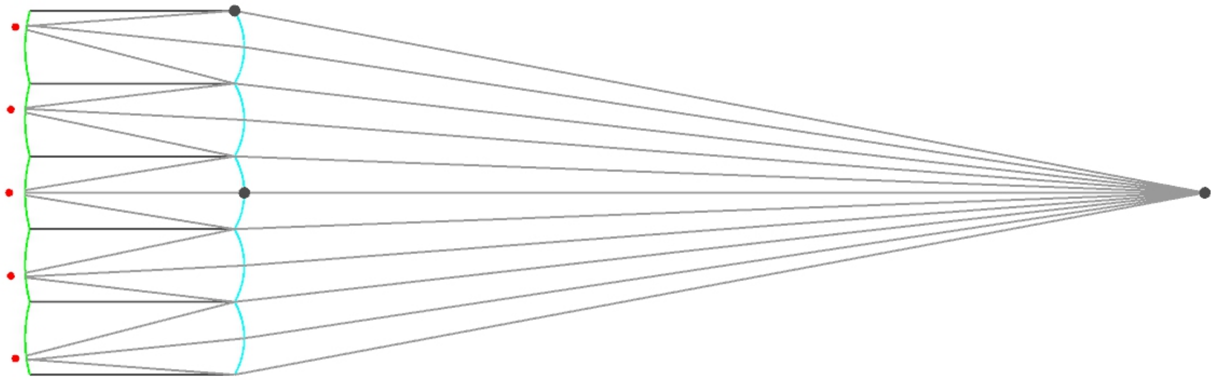
$$\frac{R}{r} + 1 = \frac{n}{n-1}$$

$$\frac{R}{r} = \frac{1}{n-1}$$

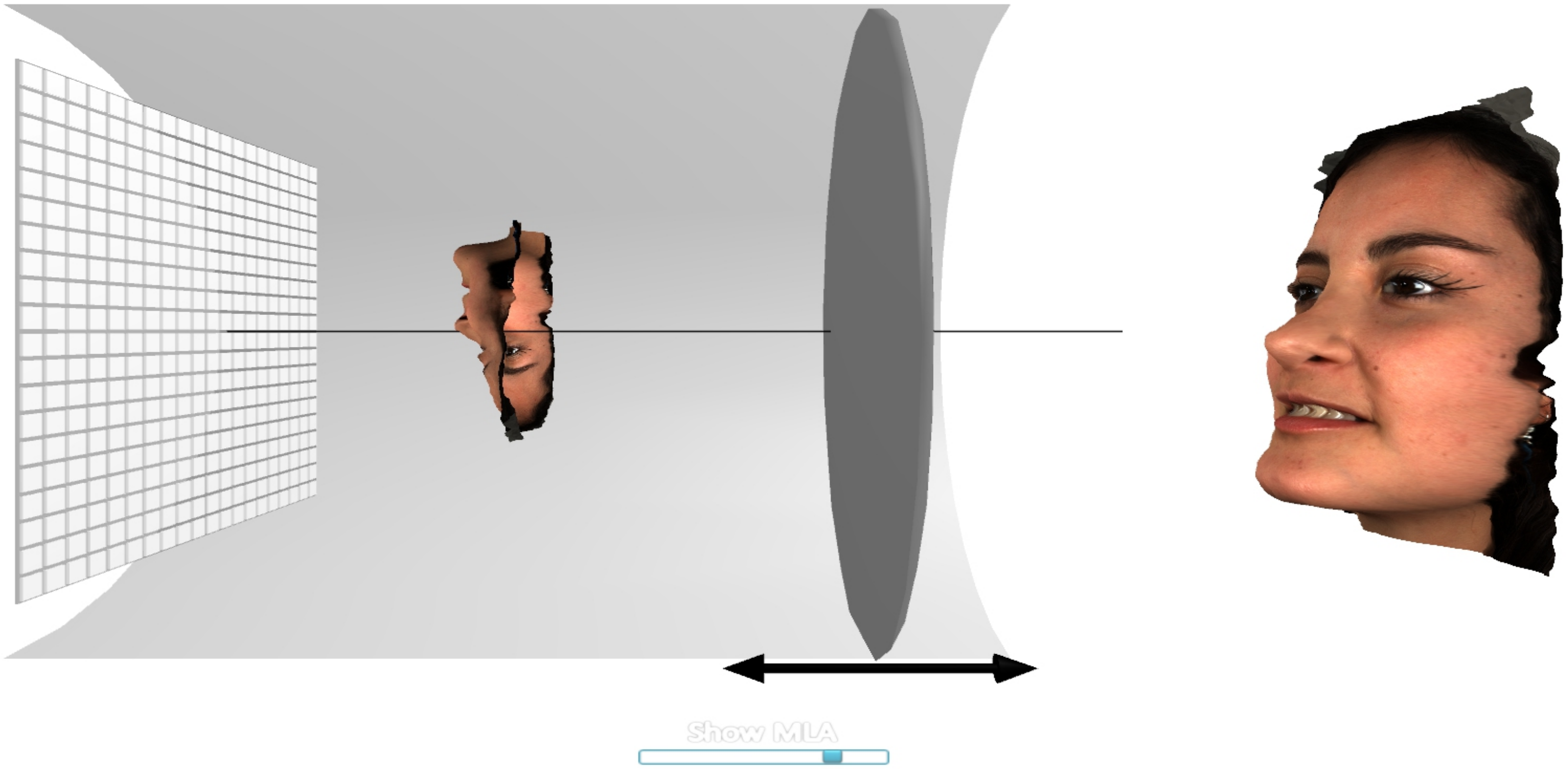
$$\frac{r}{R} = n - 1$$



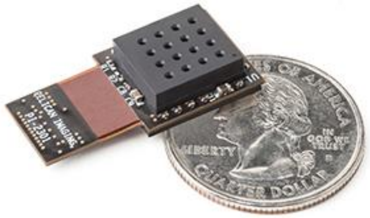
Lippmann Setup

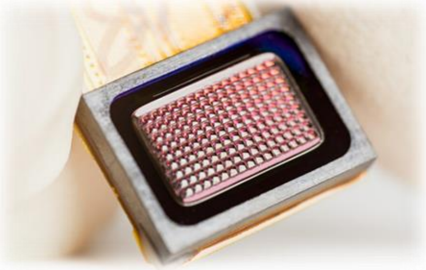


Light Field Camera



Available Devices





First Multi-View Setups

Stanford Camera Array

Point Grey Research, Inc.

ProFusion25

Array of custom cameras instead of microlens array in front of photosensor array.

Raytrix

42 MP Sensor LF-Camera

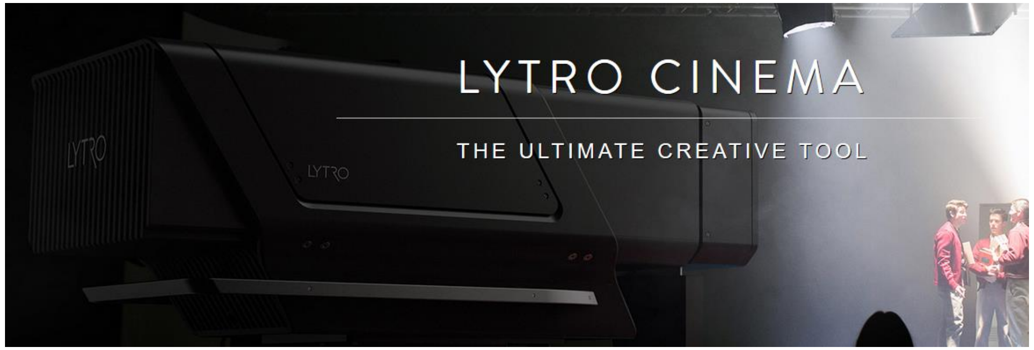
LF-Microscope

29MP Industrial LF-Camera

Lytro

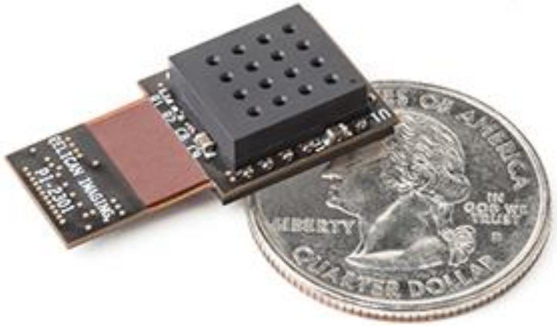
Imaging

Immerge



Cinema

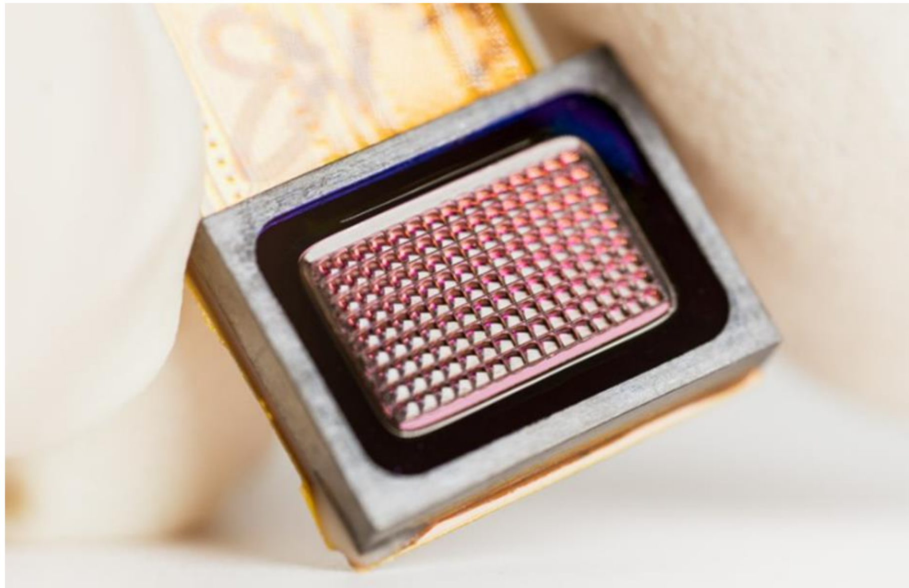
Pelican Imaging

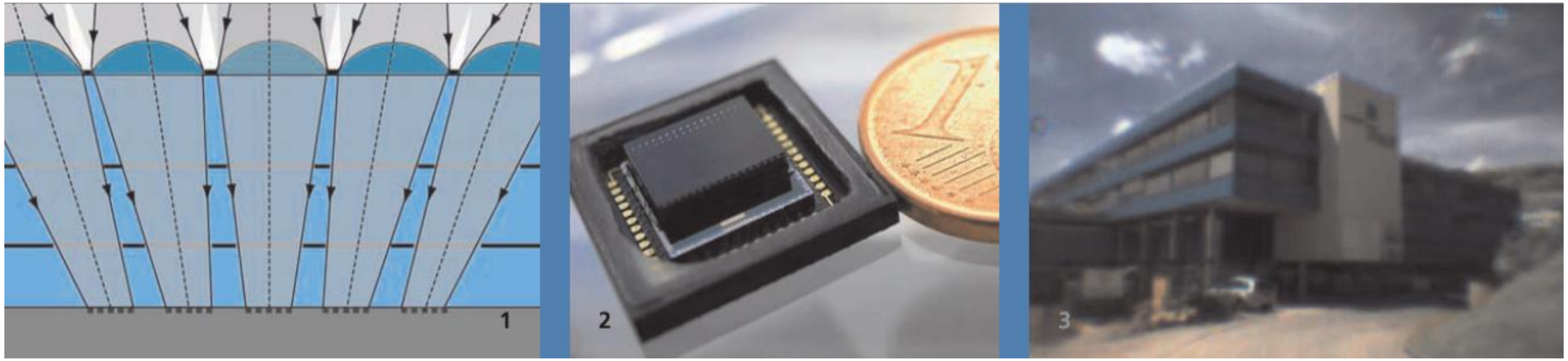


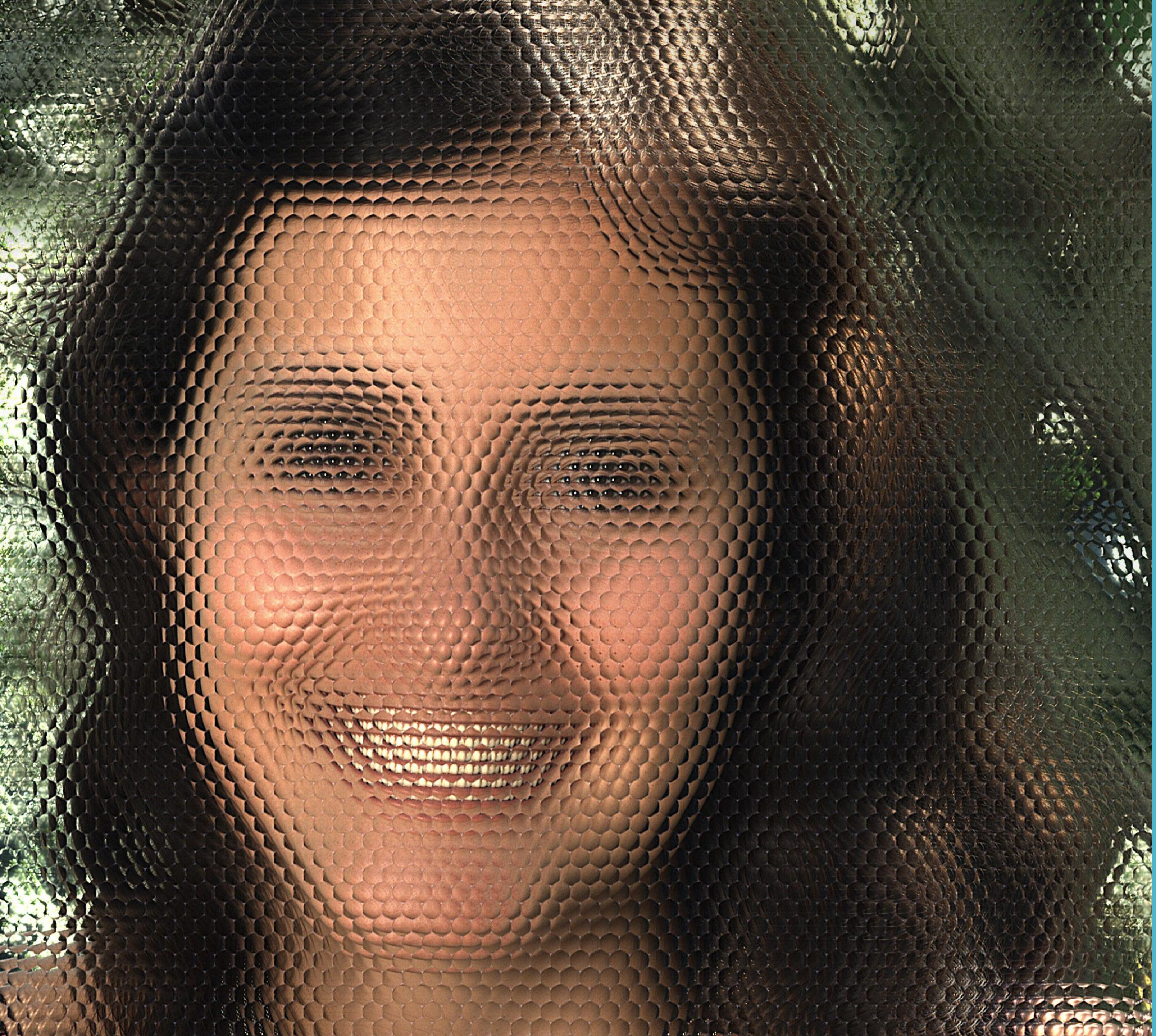
3D, HDR, RGB, Superresolution

Fraunhofer IOF

Waver level multi aperture camera

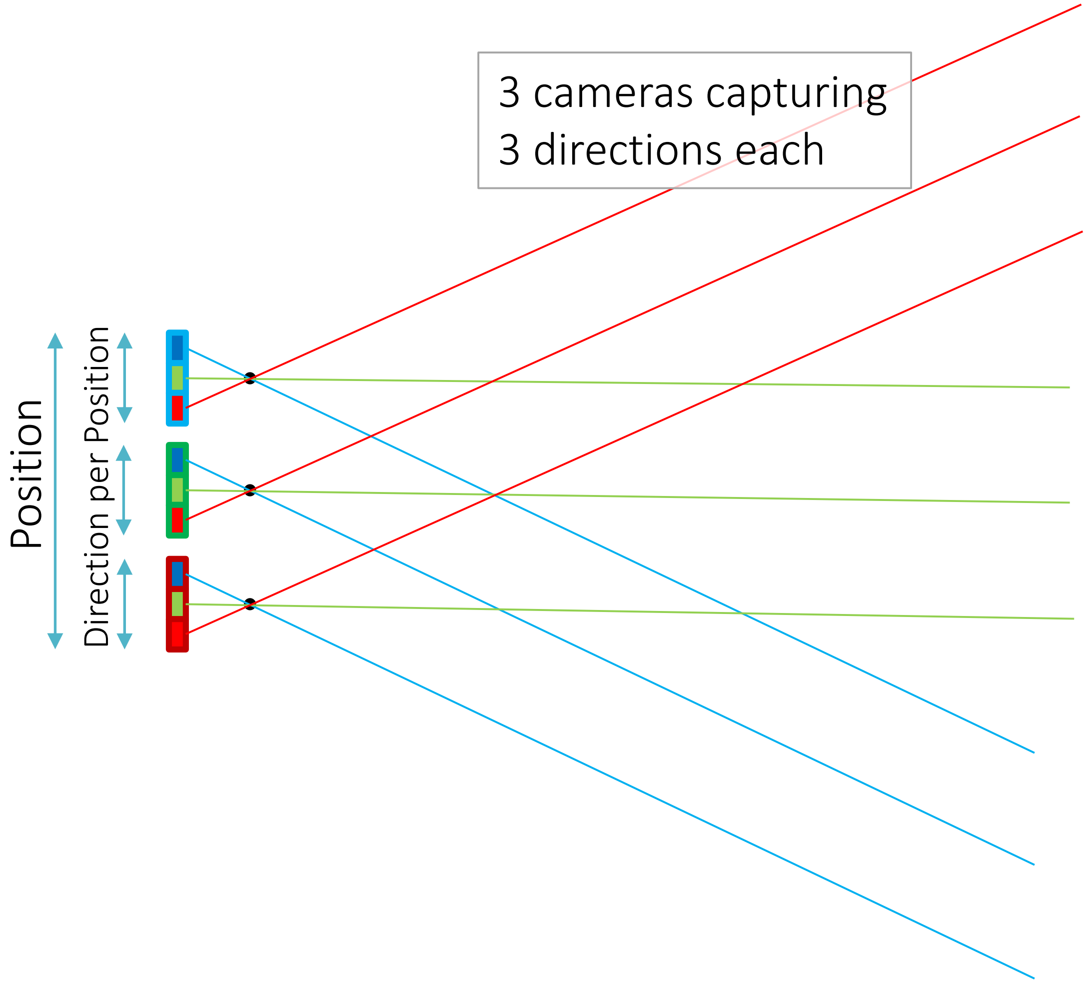


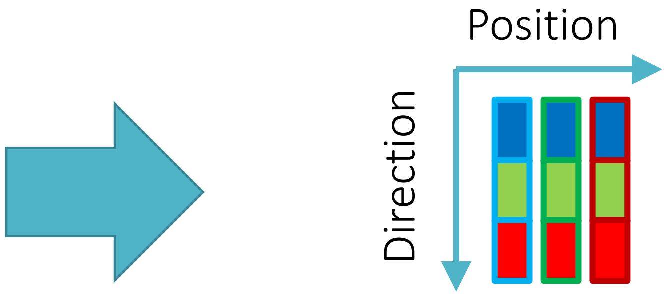




What is a Light Field?

1D Light Field Pinhole Model

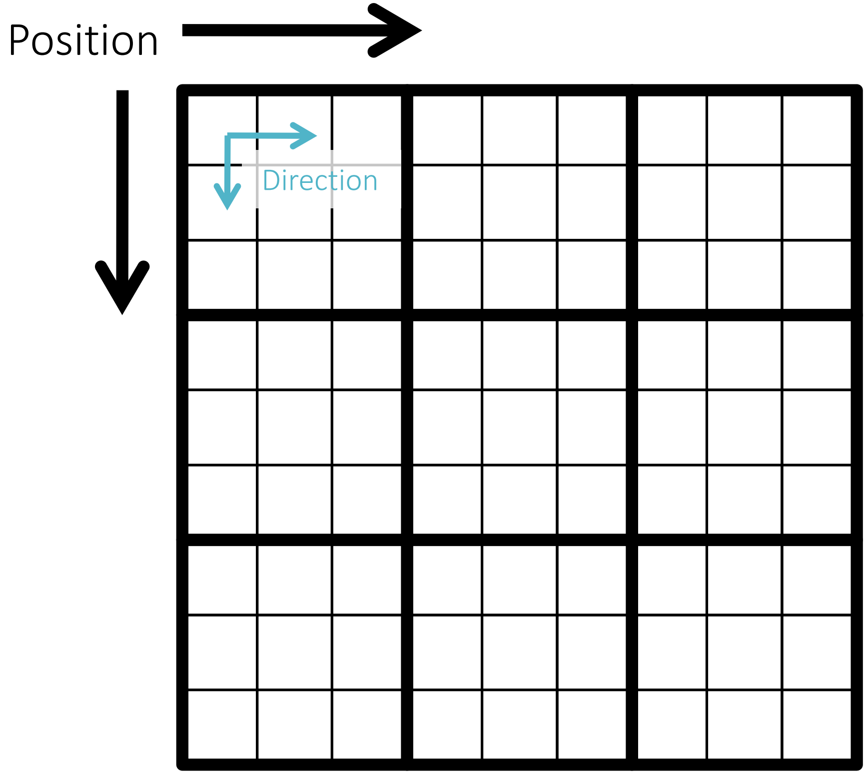


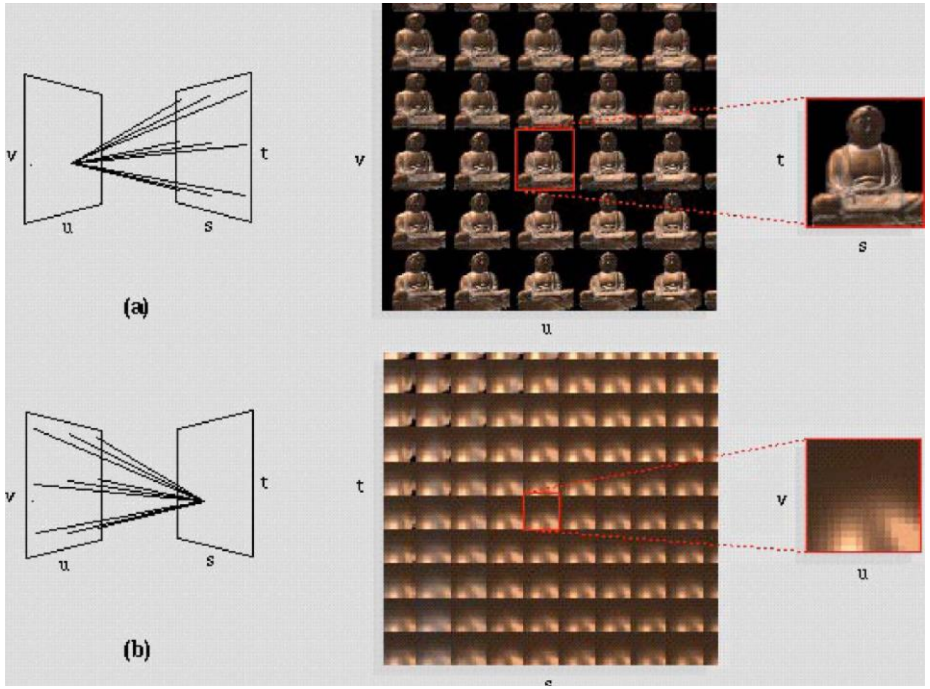


2D Light Field Pinhole Model

3x3 cameras capturing
3x3 directions each

4D Light Field

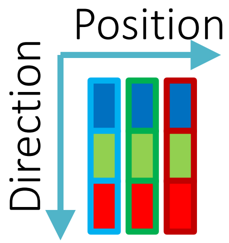


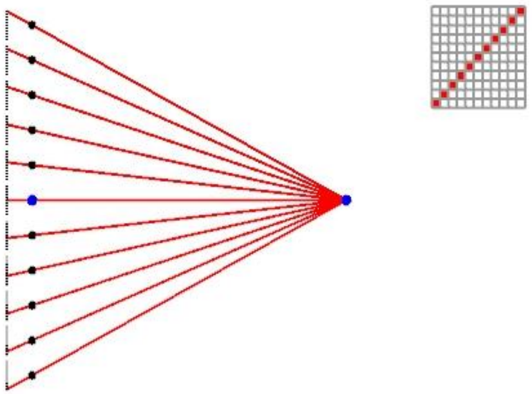


Levoy & Hanrahan

2D Light Field

A point in space is represented by a line in 2D light field space.



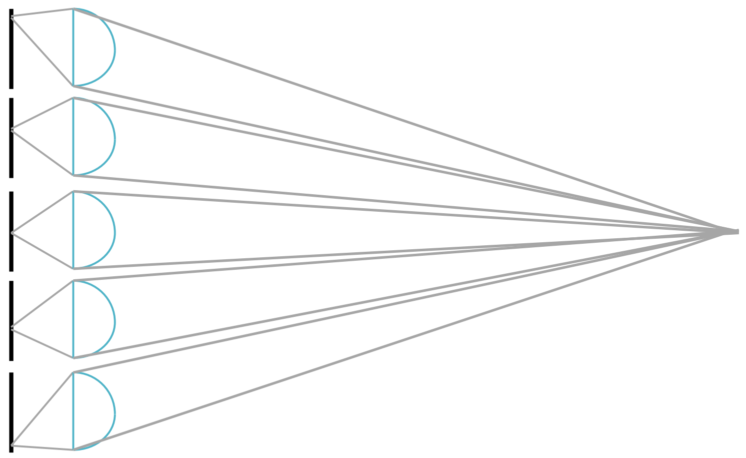


Light Field 1.0 vs. 2.0

1.0 - Unfocused

Distance between image plane and micro lens equals focal lenght of micro lens, i.e. focused to infinity.
Can synthesize image without knowledge of scene depth.

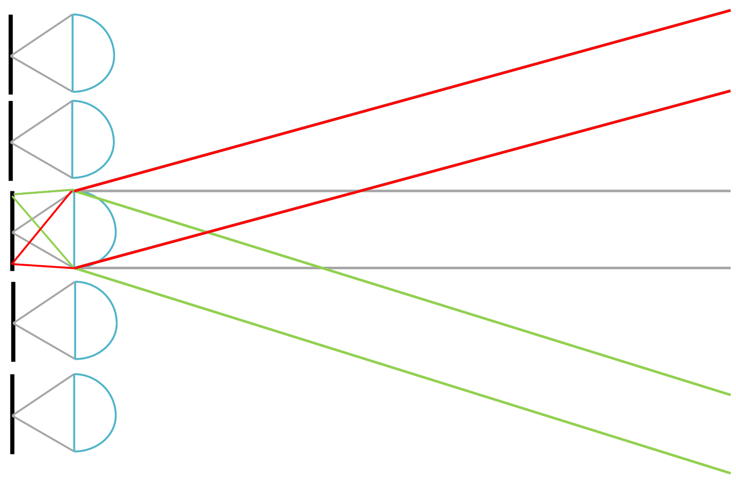
2.0 - Focused



Micro lenses are focused to a particular scene depth.
Need to know scene depth to synthesize image.

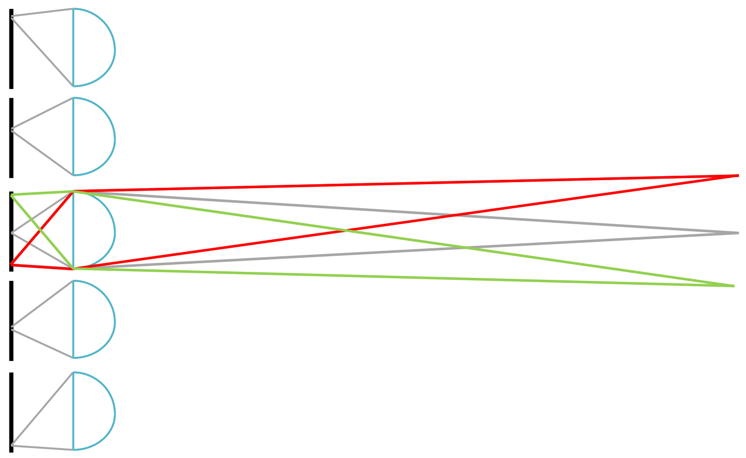
Light Field 1.0 vs. 2.0

1.0 - Unfocused



Is usually understood to mean that every micro lens sees (almost) the whole scene. In that case, the effective lateral resolution is equal to the number of micro lenses.
Directional resolution equal to number of pixels per micro lens.

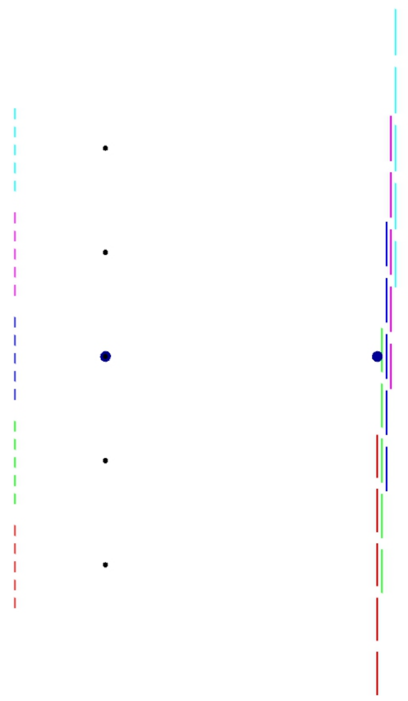
2.0 - Focused



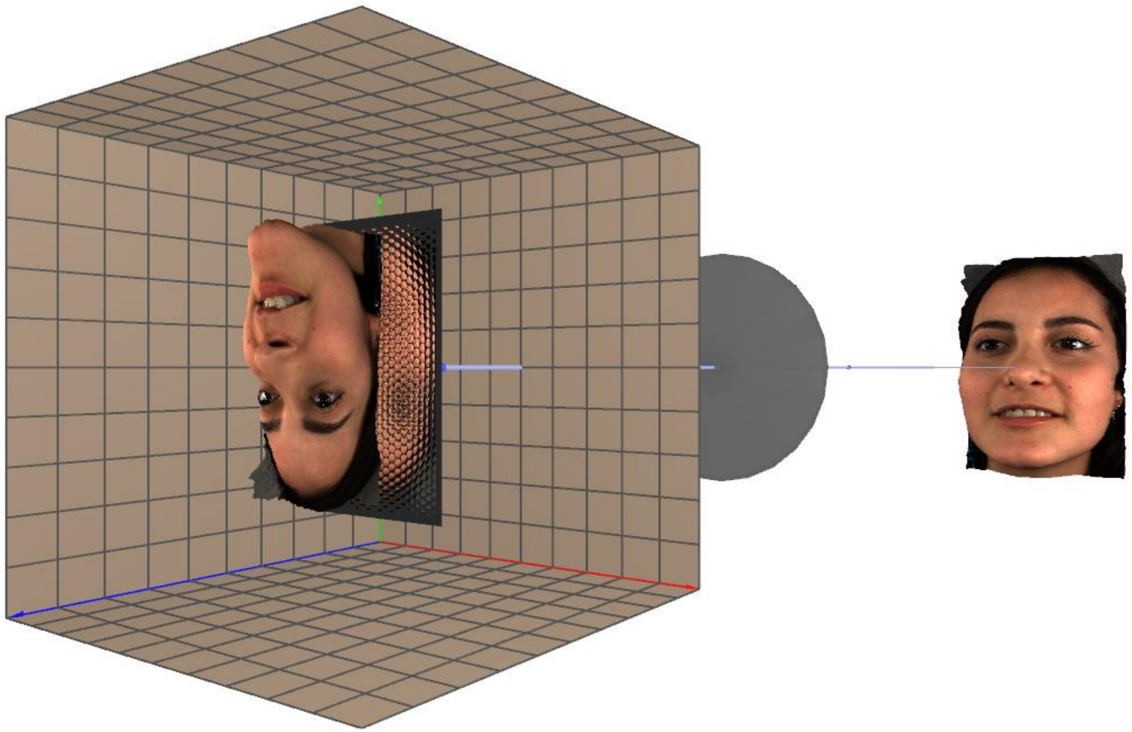
Is usually understood to mean that every micro lens sees only part of the scene.
The amount of overlap determines the effective lateral resolution which varies with depth.

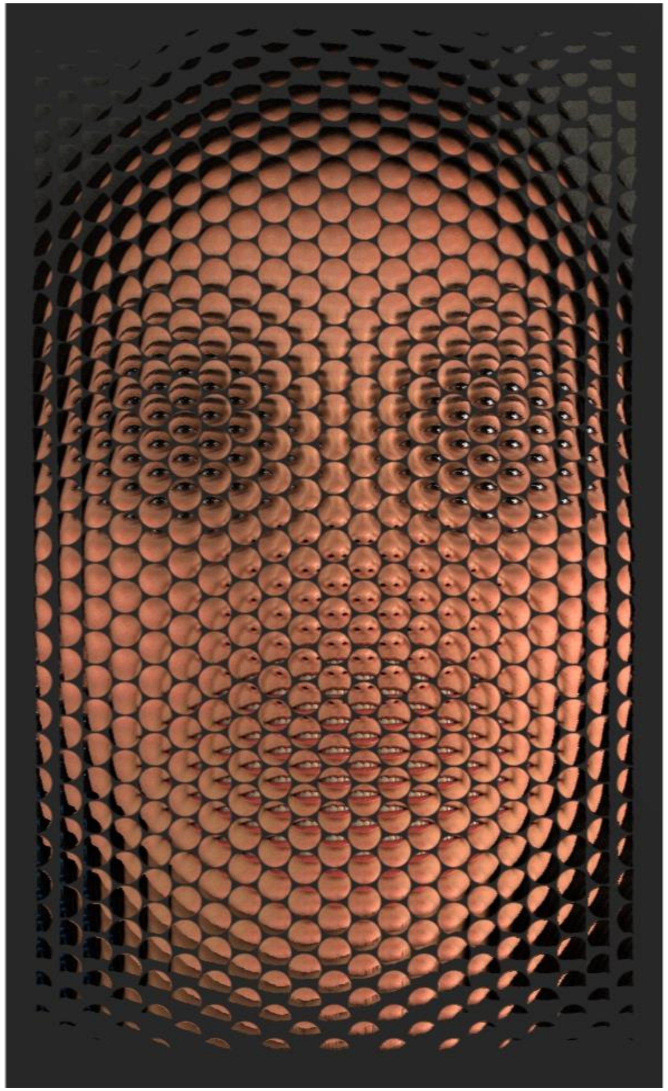
Light Field 1.0 vs. 2.0

Difference between light field 1.0 and 2.0 has nothing to do with the focus setting of the micro lenses but rather with the overlap of their field of view.



Light Field Camera Model

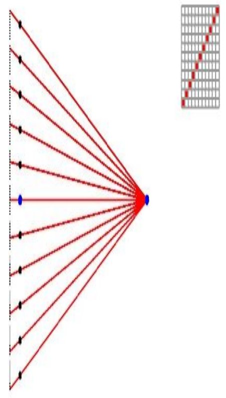


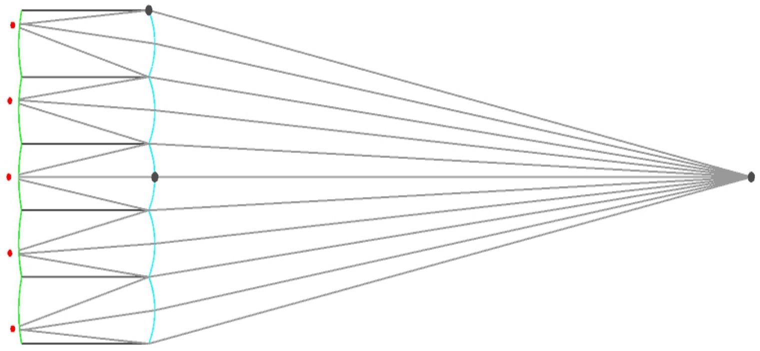


Towards a real light field camera

Pinhole vs. Lens

A real lens has a finite depth of field.
A single spherical lens does not have a perfect focus point.

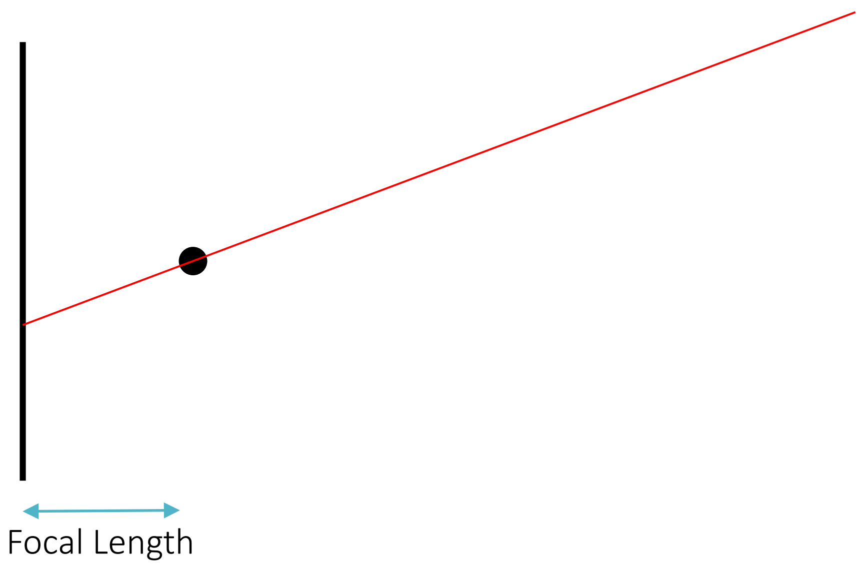




Focal Length vs. Image Distance

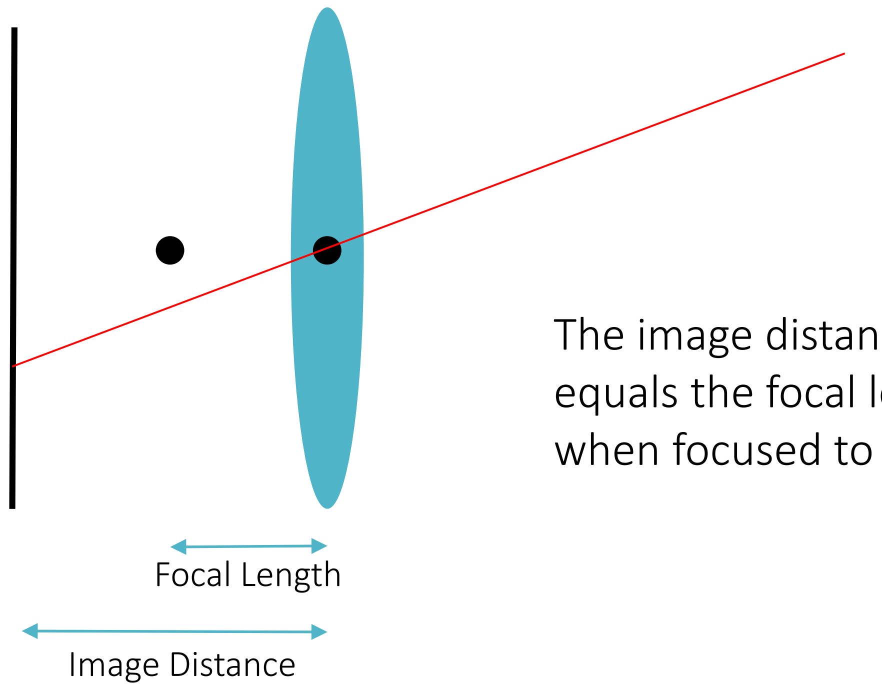
Pinhole Camera

The focal length in a pinhole camera is actually the image distance, since everything is in focus anyway.



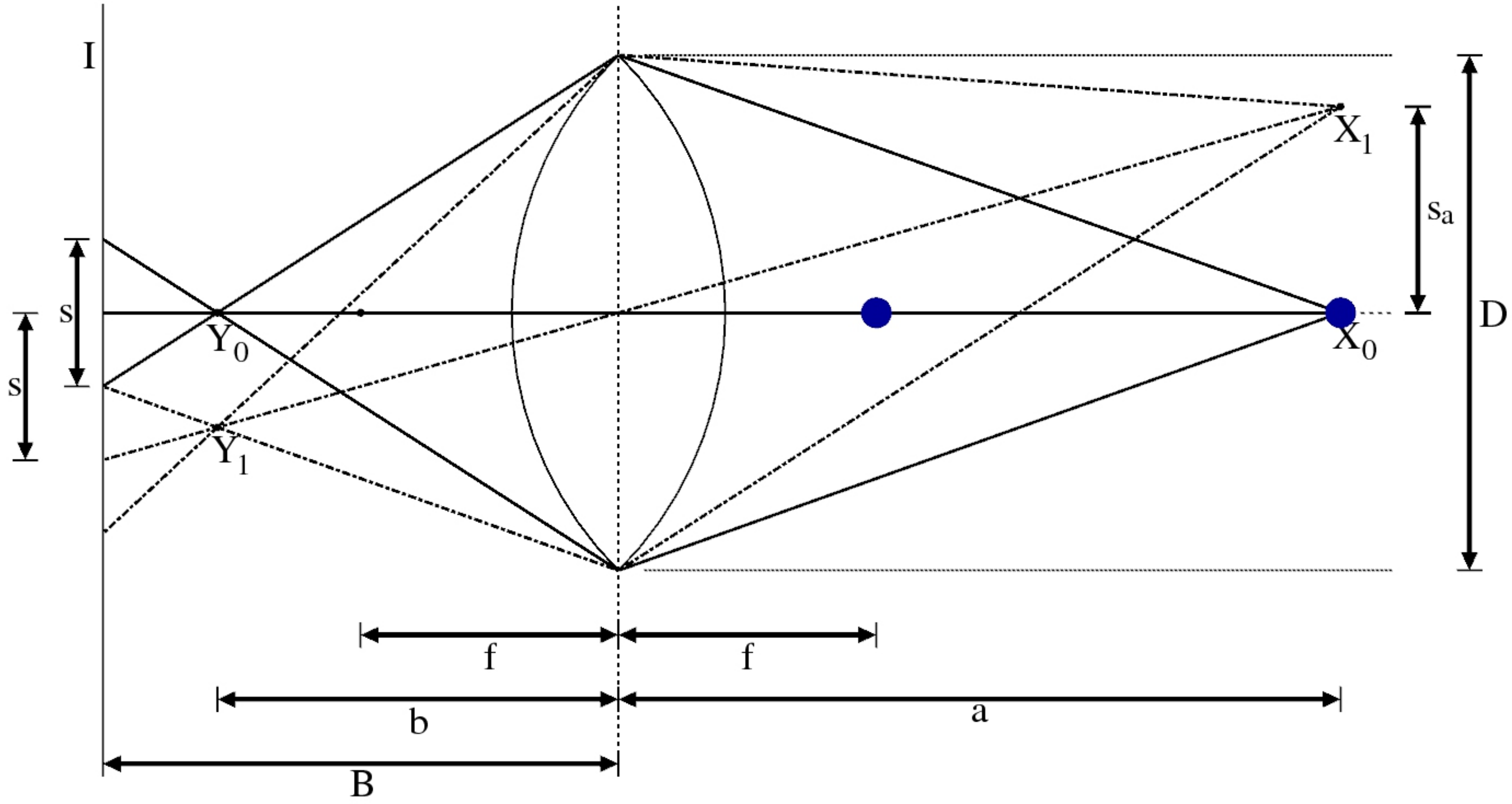
Ideal Thin Lens Camera

The image distance determines the direction of the central projection ray and the field of view. The focal length determines the focus.

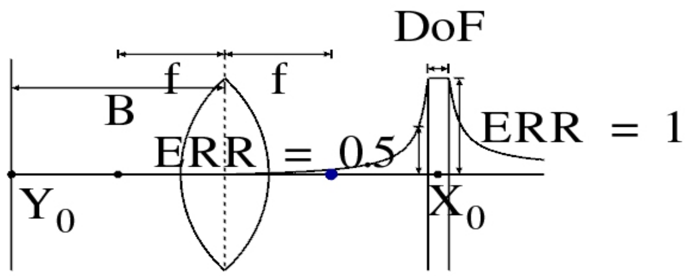


The image distance equals the focal length when focused to infinity.

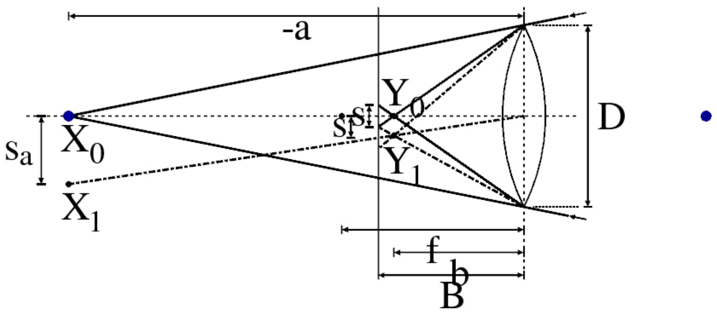
Single Lens: Depth of Field



Effective Resolution Ratio

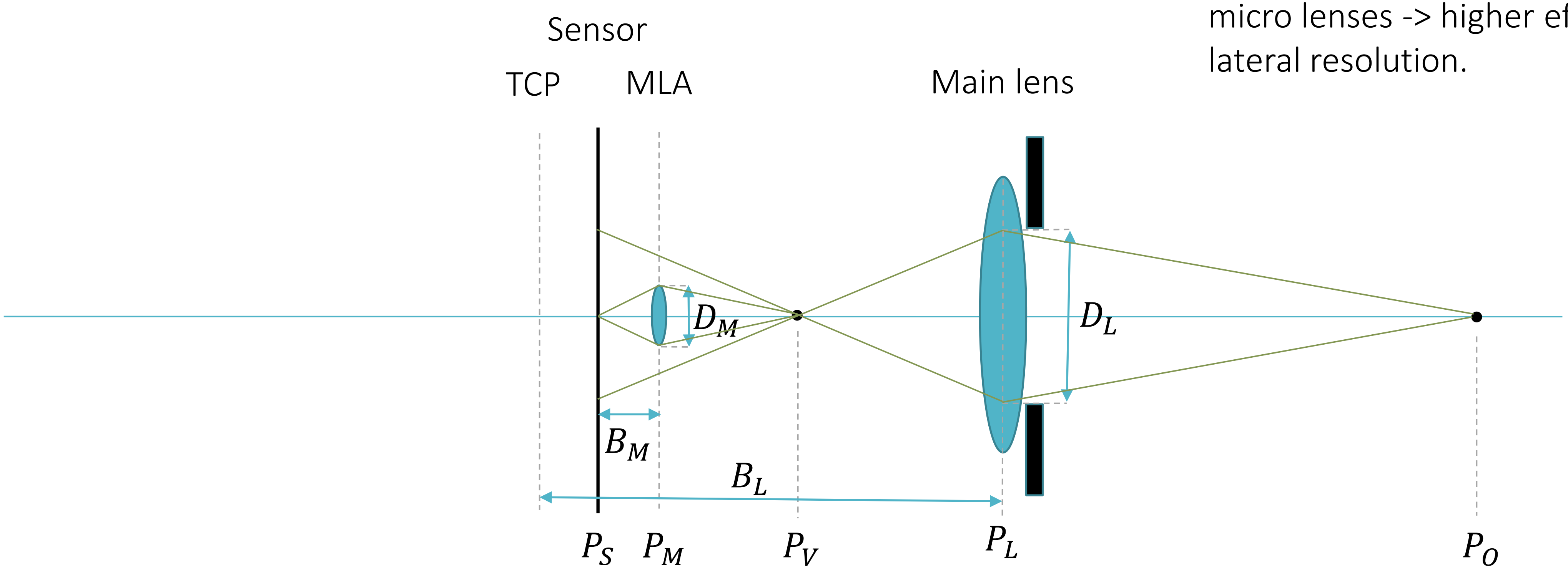


Single Lens: Virtual Image DoF

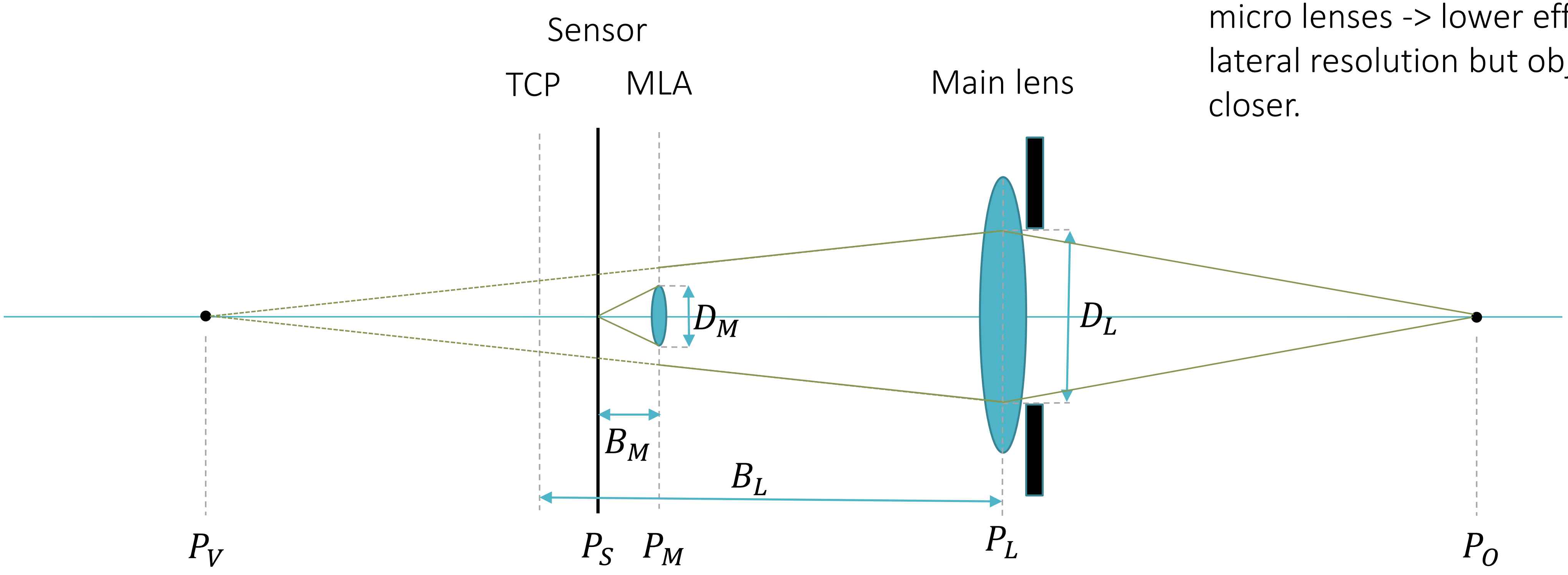


Imaging Real Image

- Typically need short focal lengths for micro lenses -> distortions
- Far away objects are imaged to many micro lenses -> low effective lateral resolution
- Near objects are imaged to fewer micro lenses -> higher effective lateral resolution.



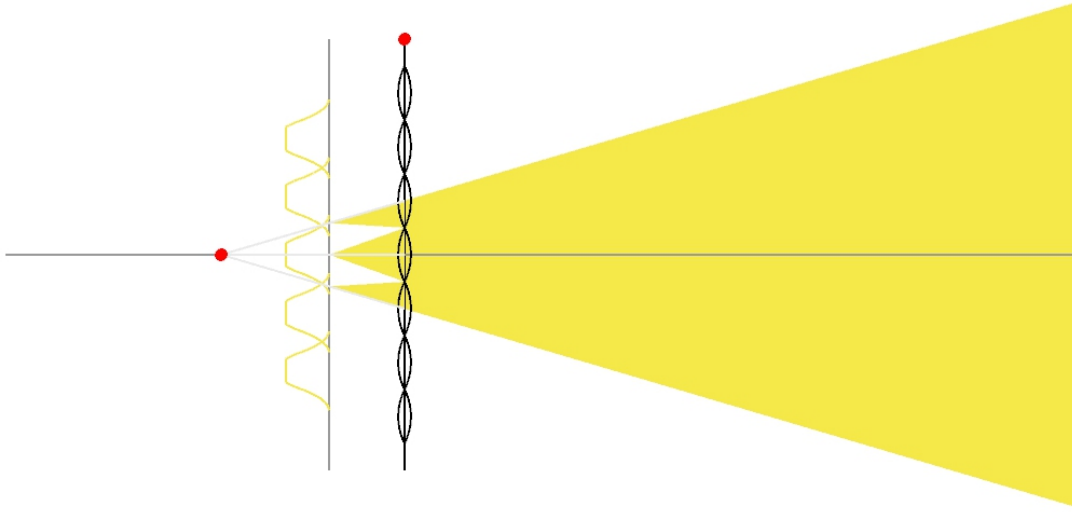
Imaging Virtual Image



- Typically need long focal lengths for micro lenses -> low distortions
- Far away objects are imaged to few micro lenses -> high effective lateral resolution
- Near objects are imaged to many micro lenses -> lower effective lateral resolution but objects are closer.

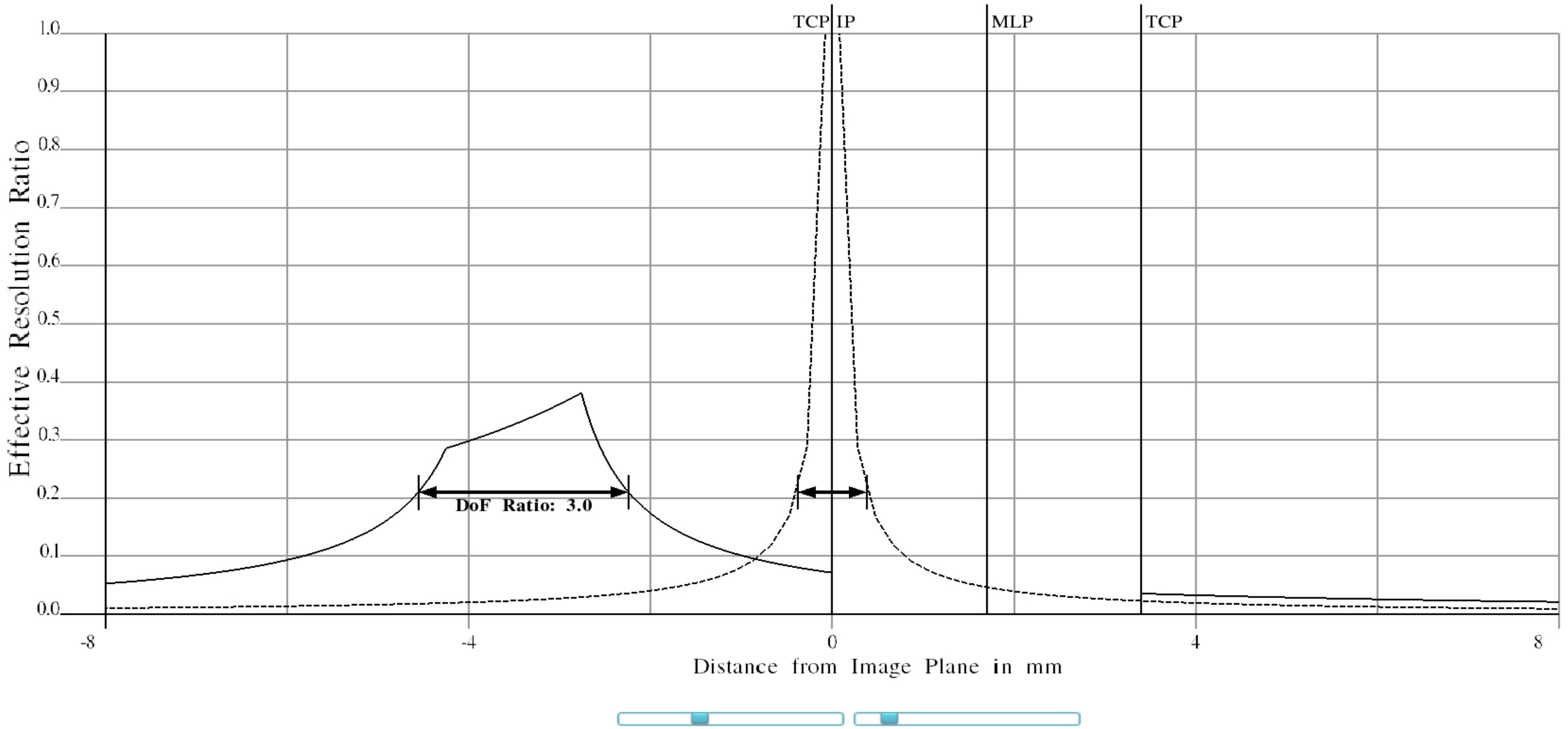
MLA: Virtual Image

- Light focused to point behind image sensor by main lens.
- The closer a point to the main lens is the further it is away from the image plane.
- The micro lens aperture has to match the main lens aperture for optimal results.



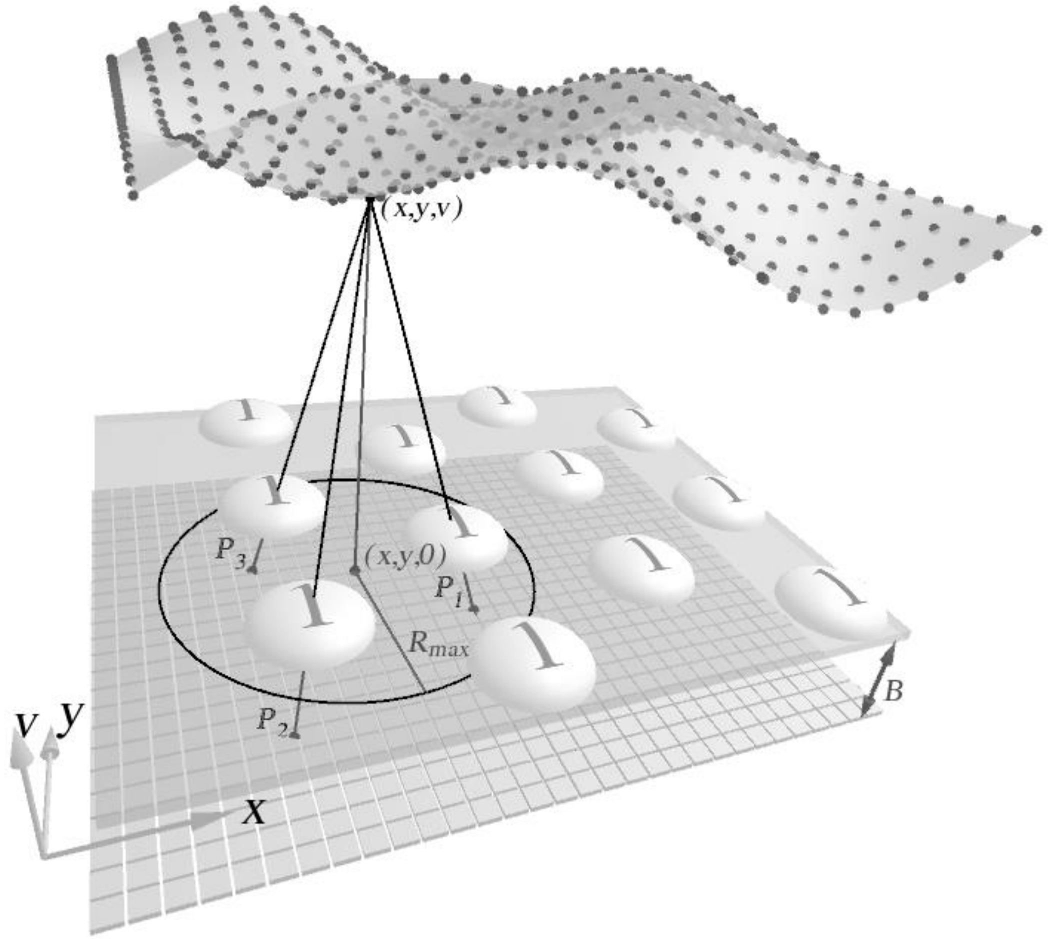
Combination of micro lens DoF and multiple imaging by micro lenses.

Light Field Camera DoF



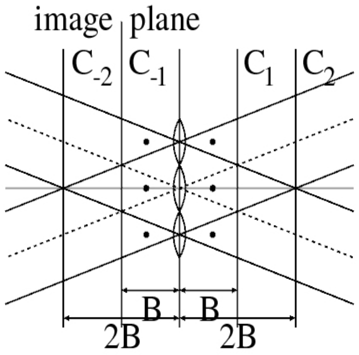
How to Design a LF-Camera

1. Determine aperture f-stop of main lens system
2. Determine how many pixels per micro lens
   a) More pixels, large diameter, multiplicity increases slowly with distance from MLA
      -> higher lateral resolution
   b) Less pixels, small diameter, multiplicity increases quickly with distance from MLA
      -> higher directional resolution
3. Microlens diameter and f-stop determine distance of micro lenses from sensor
4. Determine micro lens focal length for desired depth of field/lateral resolution.
5. Position main lens so that focal plane of furtherst desired distance projects to total covering plane.

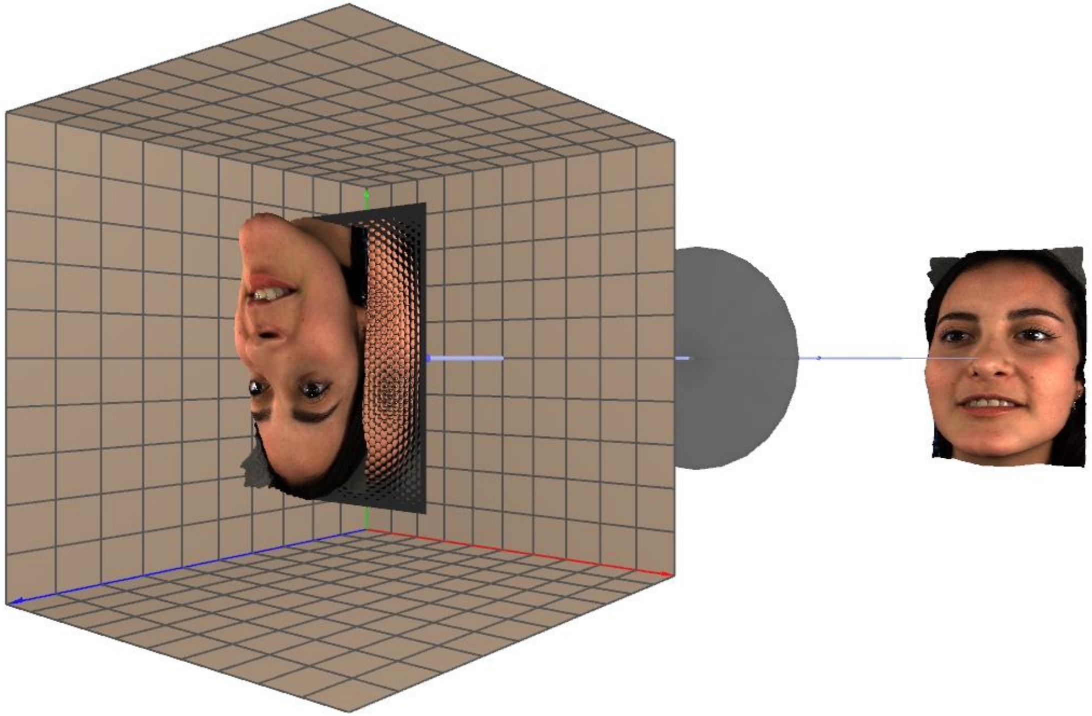


Algorithms

Multiplicity and Total Covering



Light Field Camera Model



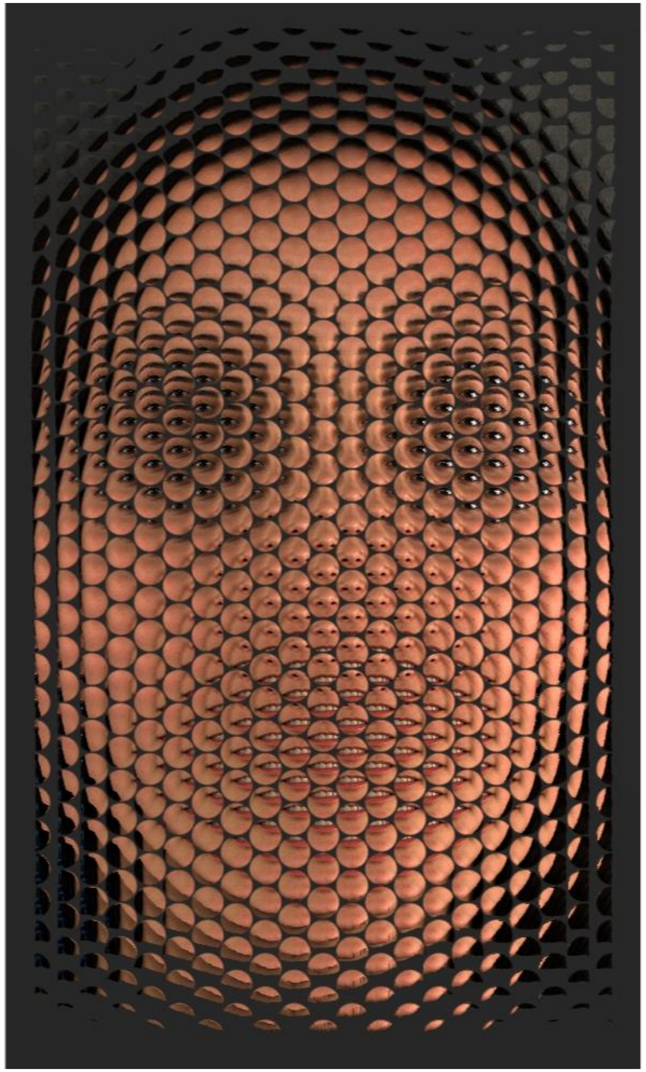
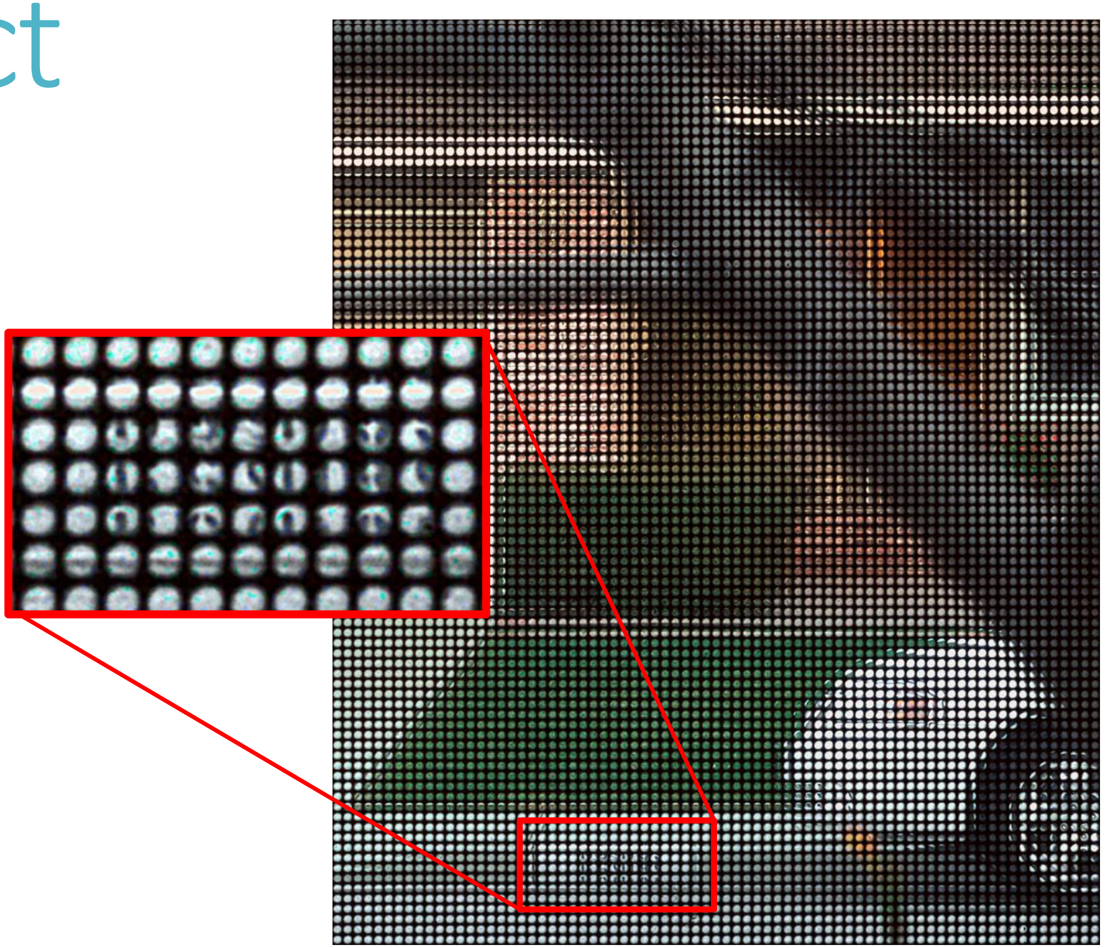


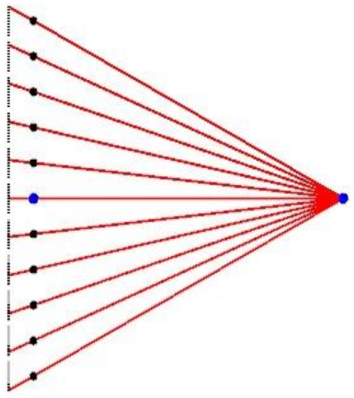
Image Synthesis: Direct

- Take one pixel from each micro image.
- Taking pixels from the same relative position in each micro lens, focuses to infinity.
- To refocus to a closer position take appropriate relative pixel positions.
- The more overlap between neighboring micro images, the better out-of-focus areas are reconstructed. Otherwise, strong artifacts can be seen.
- If depth for each point in scene were known, can generate an all in focus image.
- See example script…



Example from Todor Georgiev

Image Synthesis: Direct



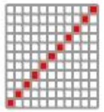
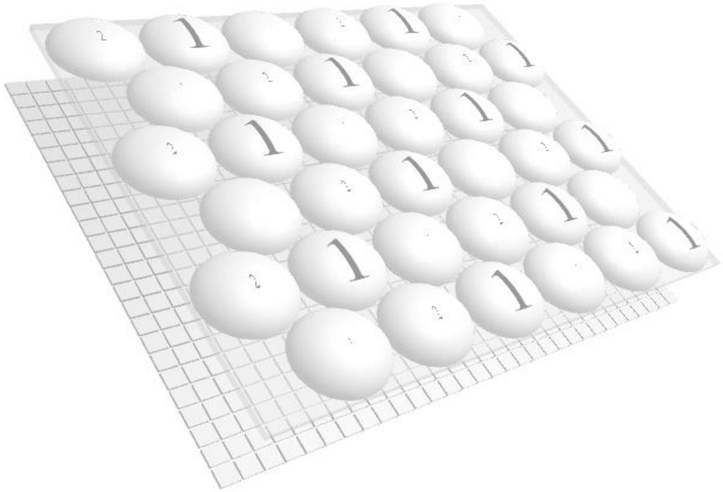


Image Synthesis: Direct 2D



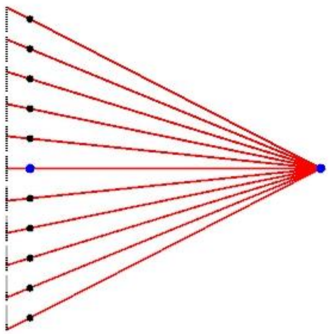
Partial MLA Cones Back Cones Front Projection

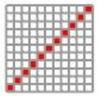
Image Synthesis: Remarks

- Simple sampling of light field gives only good results with large overlap between micro images (i.e. high directional resolution) and a large number of micro lenses. Basically a high resolution light field.
- To achieve a high effective resolution with a single camera, need to keep overlap between micro images as small as possible, while still alowing for depth calculation from raw image. A simple sampling of these sparse light fields results in strong artifacts if sampled with an incorrect depth.
- Dense light fields allow for simple sampling algorithms, while sparse light fields need more complex algorithms to achieve artifact free result images.

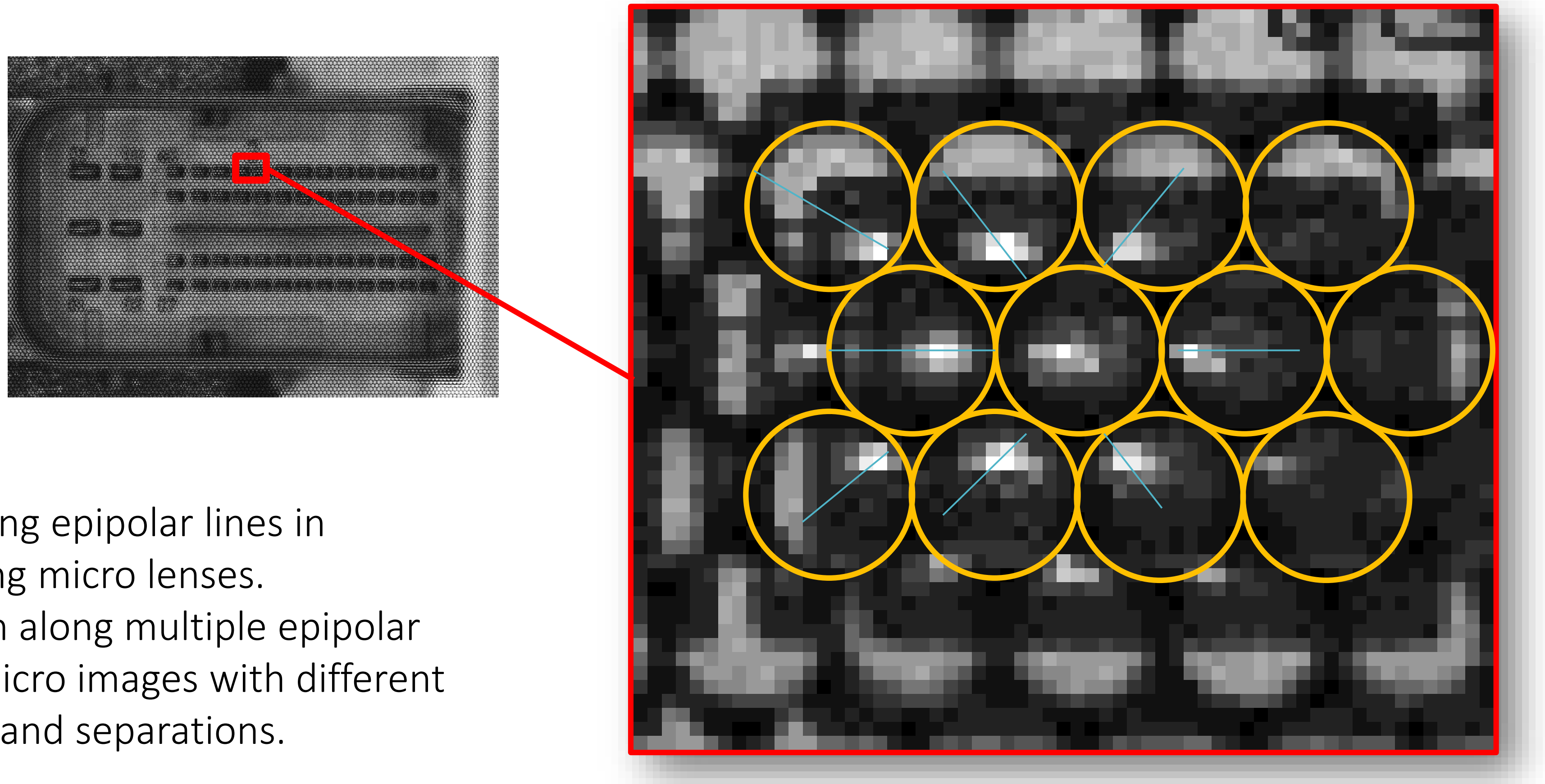
Depth from Light Field

- For dense light fields can use method of measuring angle of line fitted to structures in light field.
- For sparse light fields need to regard neighboring micro lenses as stereo camera pairs and do some standard stereo matching.





Depth from Sparse Light Field Image



- Search along epipolar lines in neighboring micro lenses.
- Can search along multiple epipolar lines for micro images with different base lines and separations.

Depth Resolution

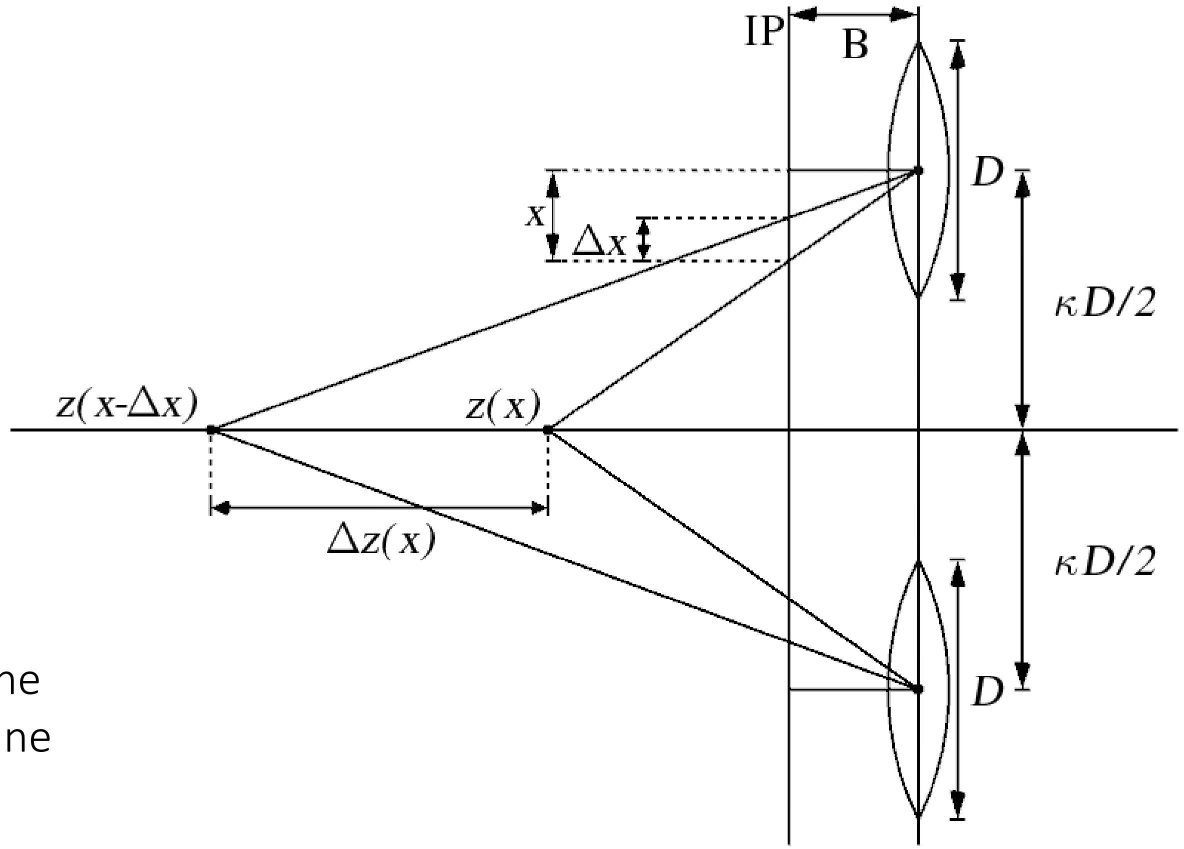
In image space:

$$z(x) = \frac{1}{x} \frac{\kappa\, B\, D}{2}$$

In object space:

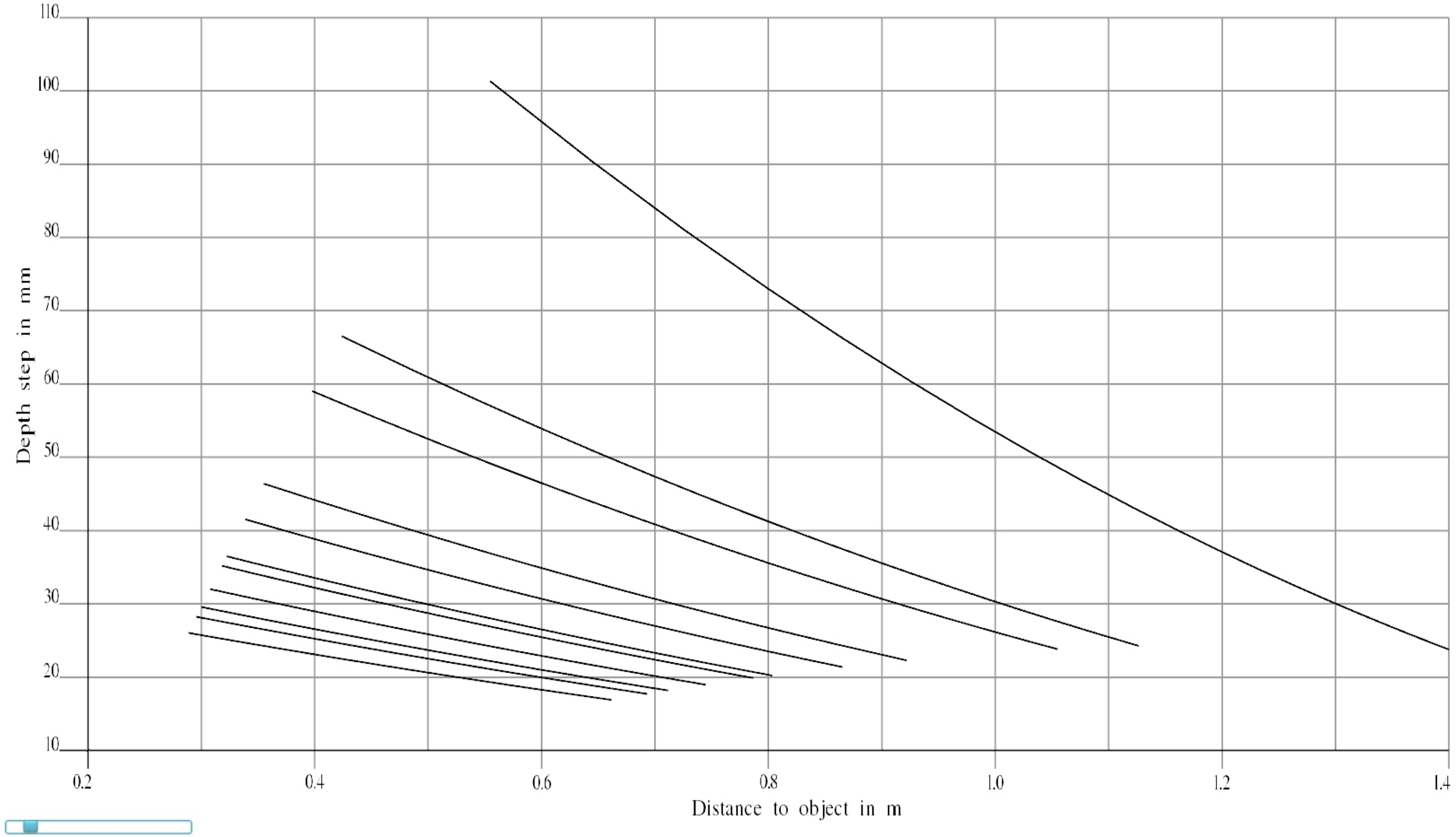
$$a(x) = \left[\frac{1}{f_L} - \frac{1}{b_0 + z(x) - z_0}\right]^{-1}$$

b_0: Distance main lens plane to Total Covering Plane
z_0: Distance micro lens plane to Total Covering Plane
f_L: Main lens focal length

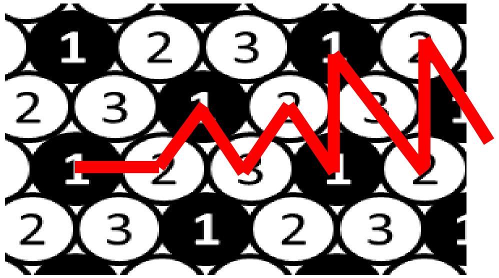


If $b_0 = f_L + z_0$ then $a(x) = x\, \frac{2\, f_L^2}{\kappa\, D\, B} + f_L$, that is the object space depth varies linearly with x.

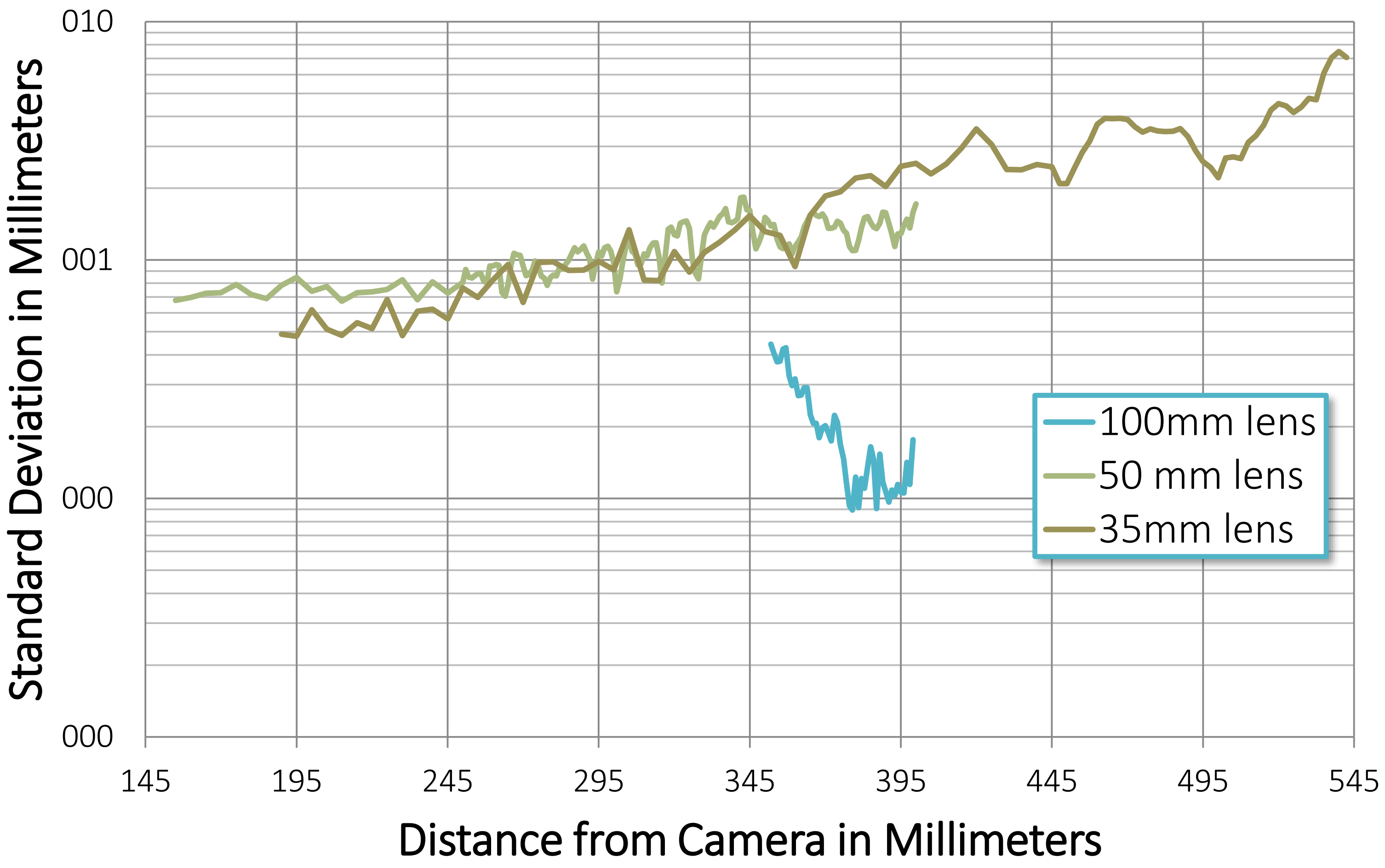
Depth Resolution per Baseline



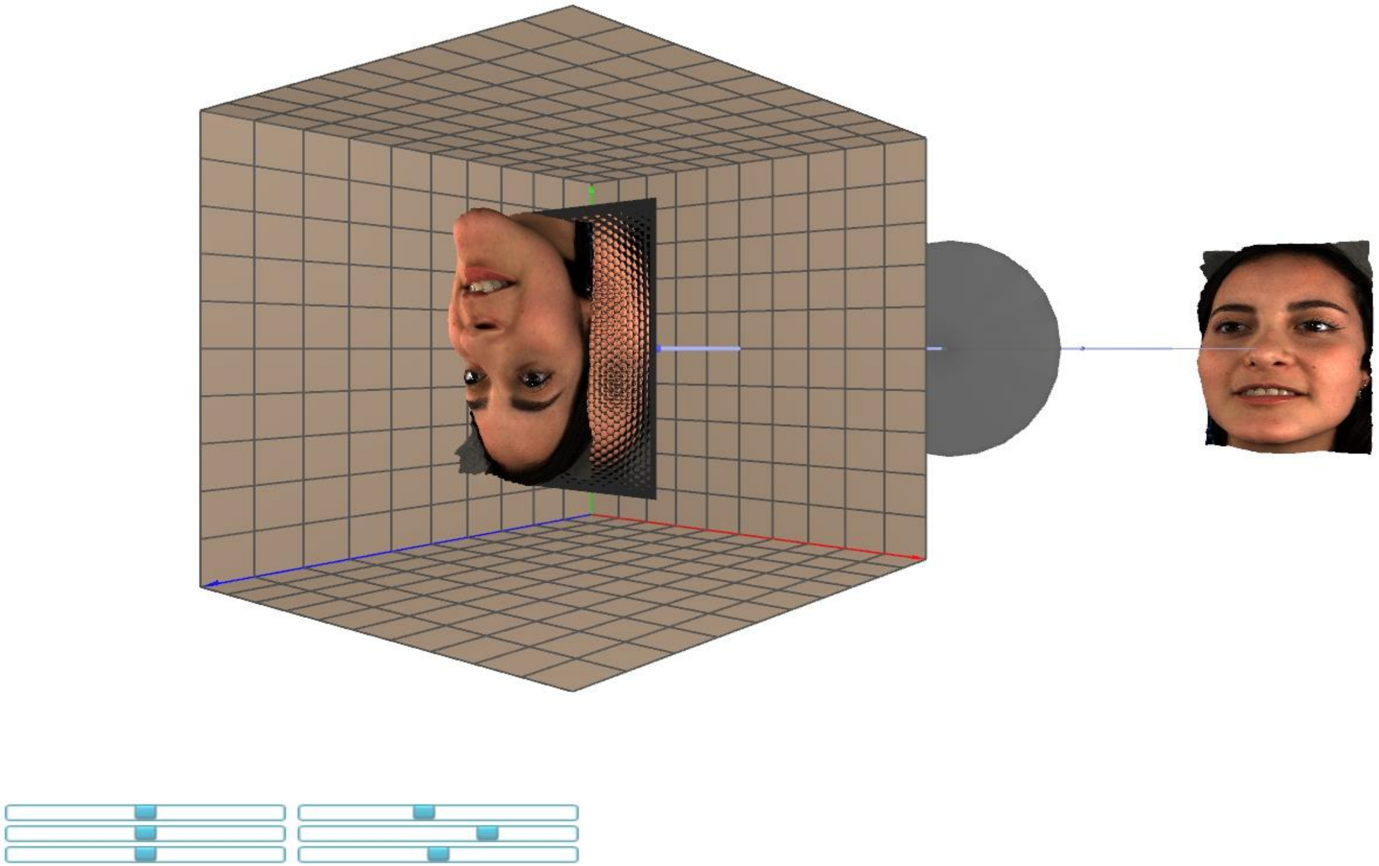
Example Camera
- Pixel Size: 10µm
- Working f-number: 8
- Focal length: 100mm
- Δx = 1 pixel

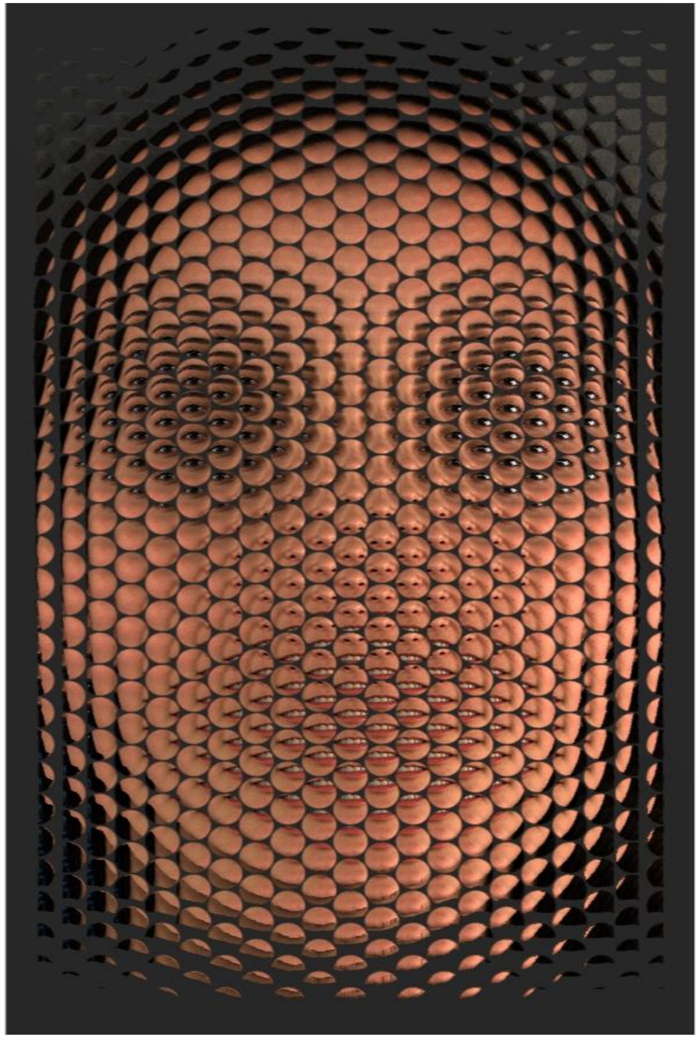


Depth Resolution Real Data



Lens Distortions





Light Field Camera Calibration

- Capture images of calibration target, e.g. checker board or point grid.
- Assume micro lenses are ideal with parallel optical axes and fixed separation.
- Calculate depth in virtual space without projection through main lens.
- Perform calibration by adaption camera model parameters until projection of virtual 3D object through main lens matches known calibration target dimensions. This is basically a 3D to 3D calibration.
- For standard cameras take multiple images of tilted calibration target at different poses.
- For microscopes move microscope perpendicular to calibration target by steps of known distance.