Lecture 34:

Light Field Cameras III

Computer Graphics and Imaging
UC Berkeley CS184/284A
Recall: What Does a 2D Photograph Record?
Aberrations Are Curvature in the Ray-Space
Aberration Correction by Adding Elements
Aberration Correction by Adding Elements

Canon 70-200mm F2.8. 23 glass elements, 3.28 lbs.
Computational Aberration Correction
In 2D Photography Can Correct Distortion

Pincushion distortion

Barrel distortion

Rectilinear

Credit: The Photoshop Creative Team
http://blog.photoshopcreative.co.uk

m43photo.blogspot.com
In 2D Photography, Cannot Correct Most Aberrations

Many aberrations exist in 3D space - spherical, coma, astigmatism, field curvature, … (many un-named)
Light Field Correction of Aberrations

Computationally redirect rays from physical trajectory to ideal location
Compute Difference Between Real and "Ideal" Imaging

(A): Aberrated ray-space  
(B): Trace rays out optically  
(C): Conjugate rays in ideally  
(D): Ideal ray-space

Figure 7.2: Ray correction function.
Compute Difference Between Real and "Ideal" Imaging

[From Kolb et al.]
Compute Difference Between Real and “Ideal” Imaging

- Real: Geometrical optics (ray-tracing, aberrations)
- Ideal: Paraxial optics (matrix methods, aberration-free)

Algorithm
- For each light field ray with radiance L
  - Compute the \((x,y,u,v)\) “real” ray inside camera
  - From real camera ray, compute corresponding “real” world ray \((x_w,y_w,u_w,v_w)\) using geometrical optics (ray-trace out through real lens system)
  - From real world ray, compute “idealized” ray inside camera from by using paraxial optics (matrix method)
  - Use “idealized” ray for image synthesis
Use Detailed Lens Formula For Ray-Tracing

Double Gauss Lens

<table>
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<tr>
<th>Radius (mm)</th>
<th>Thick (mm)</th>
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<td>48.0</td>
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From W. Smith, Modern Lens Design, p. 312
Ray Tracing Through Real Lens Designs

200 mm telephoto
35 mm wide-angle
50 mm double-gauss
16 mm fisheye

From Kolb, Mitchell and Hanrahan (1995)
Remember: 2D Unwarping for Distortion

Pincushion distortion

Barrel distortion

Rectilinear

Credit: The Photoshop Creative Team
http://blog.photoshopcreative.co.uk
4D Unwarping for General Aberrations
4D Unwarping for General Aberrations
4D Unwarping for General Aberrations
Experiment on Database of Lenses
Lens Performance Increases with Light Field Resolution

<table>
<thead>
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<th>Effective Resolution (MP)</th>
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<tbody>
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<td>0.031</td>
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10x Increase in Effective Resolution (N = 14)

Double Gauss Objective, USP 3552829

Light Field Resolution
(Number of pixels across microlens)

Effective Resolution (MP)
Lens Performance Increases with Light Field Resolution

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Design Better Lenses Assuming Light Field Imaging

Without Light Field Correction

- F2 aperture
- >3x zoom not achievable
- 16 elements total
- 3 aspheric elements

With Light Field Correction

- F2 aperture
- 8x zoom
  - 2.83x larger max focal length
  - 20% longer lens
- 13 elements total
- 0 aspheric elements
Lens Needs Computation For Good Performance
Computationally corrected
2D vs 4D Resolution With Same CMOS Sensor
2D vs 4D Resolution With Same CMOS Sensor
Light Fields Motivate Higher Sensor Resolution
4D Resolution Scaling

- More microlenses provide more vertical lines
- More pixels per microlens provide more horizontal lines
Consumer Light Field Resolutions Today

Lytro (2012)
10 MegaRay
~10 pixels / microlens

Lytro ILLUM (2014)
40 MegaRay
~14 pixels / microlens
Lytro Image Sensors

10 MP  2012
40 MP  2014
164 MP 2016
And Much Higher Resolution Sensors Are Possible

Mobile phone camera
16 MP
1.12 micron pixel
And Much Higher Resolution Sensors Are Possible

700 million pixels from a phone camera fit in this sensor area.

Full-frame sensor
50 MP
4.2 micron pixel

Credit: cameraegg.org
Pixel Readout Bandwidth is Growing Fast Too

CMOSIS CMV12000
12MP @ 300 fps
3.6 Gigapixel / sec

Forza
133 MP @ 60 fps
8.0 Gigapixel / sec
164 MP Image (2D Image, not 4D Light Field)
164 MP Image (2D Image, not 4D Light Field)
164 MP Image (2D Image, not 4D Light Field)
164 MP Image (2D Image, not 4D Light Field)
164 MegaRay Raw Light Field

Full field of view

Crop (14x14 pixels / microlens)
10 MegaRay
316 x 316 spatial
10 x 10 directional
40 MegaRay
369 x 553 spatial
14 x 14 directional
164 MegaRay
747 x 1120 spatial
14 x 14 directional
Many Ways to Capture Light Fields
Programmable Aperture (LCD)

Scan out light field one sub-aperture image at a time
High res light fields, but requires lengthy scanning

[Liang et al 2008]
Spherical Gantry $\Rightarrow$ 4D Light Field

Original light field rendering paper
Take photographs of an object from all points on an enclosing sphere
Captures all light leaving an object – like a hologram

$L(x, y, \theta, \phi)$

[Levoy & Hanrahan 1996] [Gortler et al. 1996]

Slide credit: Pat Hanrahan
Multi-Camera Array ⇒ 4D Light Field
Two-Plane Light Field

2D Array of Cameras

2D Array of Images

$L(u,v,s,t)$

Slide credit: Pat Hanrahan
Multi-Camera Array

Very large “virtual aperture.” Very flexible imaging

[Wilburn et al 2005] [Yang et al. 2002]
Light Field Video Camera Array

Very large “virtual aperture.” Very flexible imaging
[Wilburn et al 2005] [Yang et al. 2002]
Light Field Microscope

Use microlens in microscope imaging path
[Levoy et al 2006]
Mandibles of a silk worm

[Levoy et al 2006]
Fern spore

[Levoy et al, 2006]
LED Array Microscope

Scan light field by sequentially illuminating specimen with LEDs positioned at different angles

[Zheng et al 2013][Tian et al 2014]
Things to Remember

Lens aberrations

• Inevitable geometrically
• Controlling aberrations leads to complex lens designs

Computational lens aberration correction with light fields

• Correction = reproject rays assuming no aberrations

Many ways to capture light fields

• Camera arrays, in microscopes, ...