Introduction to Light Fields

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http://cameraculture.media.mit.edu/
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<td>• Interaction with Occluders</td>
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Light Fields

Goal: Representing propagation, interaction and image formation of light using purely position and angle parameters

- Radiance per ray
- Ray parameterization:
  - Position: s, x, r
  - Direction: u, θ, s
Limitations of Traditional Lightfields

rigorous but cumbersome
wave optics based

Wigner Distribution Function

Traditional Light Field

ray optics based
simple and powerful
limited in diffraction & interference

holograms
beam shaping
rotational PSF

Courtesy of Se Baek Oh. Used with permission.
Example: New Representations Augmented Lightfields

rigorous but cumbersome
wave optics based

Wigner Distribution Function

Traditional Light Field

ray optics based
simple and powerful
limited in diffraction & interference

Augmented LF

Interference & Diffraction
Interaction w/ optical elements

Non-paraxial propagation

WDF

Traditional Light Field

Courtesy of Se Baek Oh. Used with permission.
The Plenoptic Function

Q: What is the set of all things that we can ever see?
A: The Plenoptic Function (Adelson & Bergen)

Let’s start with a stationary person and try to parameterize everything that he can see…
Grayscale snapshot

• is intensity of light
  – Seen from a single view point
  – At a single time
  – Averaged over the wavelengths of the visible spectrum
• (can also do $P(x,y)$, but spherical coordinate are nicer)
Figure removed due to copyright restrictions.

\[ P(\theta,\phi,\lambda) \]

- is intensity of light
  - Seen from a single view point
  - At a single time
  - As a function of wavelength
A movie

$P(\theta, \phi, \lambda, t)$

- is intensity of light
  - Seen from a single view point
  - Over time
  - As a function of wavelength

Figure removed due to copyright restrictions.
Holographic movie

\[ P(\theta, \phi, \lambda, t, V_X, V_Y, V_Z) \]

- is intensity of light
  - Seen from ANY viewpoint
  - Over time
  - As a function of wavelength

Figure removed due to copyright restrictions.
The Plenoptic Function

\[ P(\theta, \phi, \lambda, t, V_X, V_Y, V_Z) \]

- Can reconstruct every possible view, at every moment, from every position, at every wavelength
- Contains every photograph, every movie, everything that anyone has ever seen.

Figure removed due to copyright restrictions.
Sampling Plenoptic Function (top view)
• Let’s not worry about time and color:

\[ P(\theta, \phi, V_X, V_Y, V_Z) \]

• 5D
  – 3D position
  – 2D direction

Courtesy of Rick Szeliski and Michael Cohen. Used with permission.
Ray

- No Occluding Objects

- 4D
  - 2D position
  - 2D direction

- The space of all lines in 3-D space is 4D.
Lumigraph/Lightfield - Organization

• 2D position
• 2D direction

Courtesy of Rick Szeliski and Michael Cohen. Used with permission.
• 2D position
• 2D position
• 2 plane parameterization

Courtesy of Rick Szeliski and Michael Cohen. Used with permission.
• 2D position
• 2D position
• 2 plane parameterization
Light Field = Array of (virtual) Cameras

Based on original slide by Marc Levoy. Used with permission.
Conventional versus plenoptic camera

Scene Pixel = (s,t)  Virtual Camera = (u,v)  Pixel = (s,t)

$uv$-plane  $st$-plane

Based on original slide by Marc Levoy. Used with permission.
Light Field = Array of (virtual) Cameras

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Light Field = Array of (virtual) Cameras

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Light Field = Array of (virtual) Cameras

Based on original slide by Marc Levoy. Used with permission.
Light Field Inside a Camera

Subject -> Main lens -> Photosensor

Courtesy of Ren Ng. Used with permission.
Light Field Inside a Camera

Lenslet-based Light Field camera

[Adelson and Wang, 1992, Ng et al. 2005 ]

Courtesy of Ren Ng. Used with permission.
Stanford Plenoptic Camera [Ng et al 2005]

Contax medium format camera

Kodak 16-megapixel sensor

Adaptive Optics microlens array

125μ square-sided microlenses

Courtesy of Ren Ng. Used with permission.

\[
4000 \times 4000 \text{ pixels} \div 292 \times 292 \text{ lenses} = 14 \times 14 \text{ pixels per lens}
\]
Digital Refocusing

Courtesy of Ren Ng. Used with permission.

[Ng et al 2005]
Adaptive Optics

- A deformable mirror can be used to correct wavefront errors in an astronomical telescope.

Shack Hartmann wavefront sensor (commonly used in Adaptive optics).

Measuring shape of wavefront = Lightfield Capture

- http://www.cvs.rochester.edu/williamslab/r_shackhartmann.html

The spots formed on the CCD chip for the eye will be displaced because the wavefront will hit each lenslet at an angle rather than straight on.

Courtesy of David Williams Lab @ the Center for Visual Science, University of Rochester. Used with permission.
Example using 45 cameras
[Vaish CVPR 2004]

Synthetic aperture videography

Image removed due to copyright restrictions.
Visualizing Lightfield

(i) Position-angle space
(ii) Phase-space
(iii) Space- Spatial Frequency
(iv) Spectrogram
\[ x_1' = x_1 + \theta_i * z \]
Light Field = Array of (virtual) Cameras
Three ways to capture LF inside a camera

- Shadows using pin-hole array
- Refraction using lenslet array
- Heterodyning using masks
Sub-Aperture = Pin-hole + Prism

**Fig. 1.** Two methods of making parallax panoramagram negatives. (a) A moving lens exposing a sensitive plate behind a grating slightly separated from it; lens, grating and plate being maintained in line during the exposure. (b) A large stationary lens, projecting an image on a stationary plate through a grating slightly separated from it.
vertical axis than is called for by the simple formula above developed. This correction, which is roughly proportional to the cosine of the angle between \( \alpha \) and the sensitive surface, and so is of importance only for large angles, also varies with the angle of observation. A diameter of taking lens and size of picture can theoretically be attained such that this second order correction will fail. The slightly greater magnification of the viewing grating called for over the amount given by the
Lens Glare Reduction
[Raskar, Agrawal, Wilson, Veeraraghavan SIGGRAPH 2008]

Glare/Flare due to camera lenses reduces contrast
Reducing Glare

Conventional Photo

After removing outliers
Glare Reduced Image

Light Field Inside a Camera

Lenslet-based Light Field camera

[Adelson and Wang, 1992, Ng et al. 2005 ]

Courtesy of Ren Ng. Used with permission.
Prototype camera

Contax medium format camera

Kodak 16-megapixel sensor

Adaptive Optics microlens array

125μ square-sided microlenses

Courtesy of Ren Ng. Used with permission.

\[
4000 \times 4000 \text{ pixels} \div 292 \times 292 \text{ lenses} = 14 \times 14 \text{ pixels per lens}
\]
Zooming into the raw photo

Courtesy of Ren Ng. Used with permission.
Digital Refocusing

Can we achieve this with a Mask alone?

Courtesy of Ren Ng. Used with permission.

[Ng et al 2005]
Mask based Light Field Camera

[Veeraraghavan, Raskar, Agrawal, Tumblin, Mohan, Siggraph 2007]
How to Capture 4D Light Field with 2D Sensor?

What should be the pattern of the mask?
Lens Copies the Lightfield of Conjugate Plane

Object

Main Lens

1D Sensor

θ-plane

x-plane

x

x₀

θ

θ₀
Line Integral

Captured Photo
Line Integral

Captured Photo
Fourier Slice Theorem

- **1-D FFT**
- **2-D FFT**
- **Central Slice**
- **Line Integral**
- **Captured Photo**
- **FFT of Captured Photo**

### Equations

- \( l(x, \theta) \)
- \( f_x \)
- \( f_{\theta} \)
- \( L(f_x, f_{\theta}) \)
Light Propagation (Defocus Blur)

Captured Photo

Line Integral

Central Slice

FFT of Captured Photo

2-D FFT

1-D FFT
Out of Focus Photo: Open Aperture
Coded Aperture Camera

The aperture of a 100 mm lens is modified

Insert a **coded mask** with chosen binary pattern

Rest of the camera is unmodified
Out of Focus Photo: Coded Aperture
Modeling and Synthesis of Aperture Effects in Cameras

Douglas Lanman, Ramesh Raskar, and Gabriel Taubin

Computational Aesthetics 2008
20 June, 2008
Slides removed due to copyright restrictions. See this paper and associated presentation at http://mesh.brown.edu/dlanman/research.html
Cosine Mask Used

Mask Tile

$\frac{1}{f_0}$
Extra sensor bandwidth cannot capture extra *angular dimension* of the light field

![Diagram showing Fourier Light Field Space (Wigner Transform)]
Sensor Slice captures entire Light Field

Modulation Function

Modulated Light Field
Where to place the Mask?

Mask

Sensor

Mask Modulation Function
Computing 4D Light Field

2D Sensor Photo, 1800*1800

2D Fourier Transform, 1800*1800

2D FFT

9*9 = 81 spectral copies

Rearrange 2D tiles into 4D planes
200*200*9*9

4D Light Field
200*200*9*9

\[ x_1' = x_1 + \theta_i z \]
Light Propagation (Defocus Blur)

Captured Photo

Line Integral

2-D FFT

Central Slice

FFT of Captured Photo
**Plenoptic Camera**
- Samples individual rays
- Predefined spectrum for lenses
- Chromatic aberration
- High alignment precision
- Peripheral pixels wasted pixels
- Negligible Light Loss

**Heterodyne Camera**
- Samples coded combination of rays
- Supports any wavelength
- Reconfigurable f/#, Easier alignment
- No wastage
- High resolution image for parts of scene in focus
- 50 % Light Loss due to mask
Space of LF representations
Time-frequency representations
Phase space representations
Quasi light field

Other LF representations
Rihaczek Distribution Function

Observable LF
Traditional light field
Augmented LF
WDF

incoherent
coherent

Courtesy of Se Baek Oh. Used with permission.
Quasi light fields
the utility of light fields, the versatility of Maxwell

We form coherent images by
formulating,
capturing,
and integrating
quasi light fields.

Courtesy of Se Baek Oh. Used with permission.
(i) Observable Light Field

- Move aperture across plane
- Look at directional spread
- Continuous form of plenoptic camera

Scene

Aperture position \( s \)

Direction \( u \)

Courtesy of Se Baek Oh. Used with permission.
(ii) Augmented Light Field with LF Transformer

Interaction at the optical elements

Courtesy of Se Baek Oh. Used with permission.
Virtual light projector with real valued (possibly negative) radiance along a ray.
(ii) ALF with LF Transformer

Courtesy of Se Baek Oh. Used with permission.
Tradeoff between cross-interference terms and localization

(i) Spectrogram
  non-negative localization

(ii) Wigner
  localization cross terms

(iii) Rihaczek
  localization complex

Courtesy of Se Baek Oh. Used with permission.
## Property of the Representation

<table>
<thead>
<tr>
<th>Representation</th>
<th>Constant along rays</th>
<th>Non-negativity</th>
<th>Coherence</th>
<th>Wavelength</th>
<th>Interference Cross term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional LF</td>
<td>always constant</td>
<td>always positive</td>
<td>only incoherent</td>
<td>zero</td>
<td>no</td>
</tr>
<tr>
<td>Observable LF</td>
<td>nearly constant</td>
<td>always positive</td>
<td>any coherence state</td>
<td>any</td>
<td>yes</td>
</tr>
<tr>
<td>Augmented LF</td>
<td>only in the paraxial region</td>
<td>positive and negative</td>
<td>any</td>
<td>any</td>
<td>yes</td>
</tr>
<tr>
<td>WDF</td>
<td>only in the paraxial region</td>
<td>positive and negative</td>
<td>any</td>
<td>any</td>
<td>yes</td>
</tr>
<tr>
<td>Rihaczek DF</td>
<td>no; linear drift</td>
<td>complex</td>
<td>any</td>
<td>any</td>
<td>reduced</td>
</tr>
</tbody>
</table>

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## Benefits & Limitations of the Representation

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<th></th>
<th>Ability to propagate</th>
<th>Modeling wave optics</th>
<th>Simplicity of computation</th>
<th>Adaptability to current pipe line</th>
<th>Near Field</th>
<th>Far Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional LF</td>
<td>x-shear</td>
<td>no</td>
<td>very simple</td>
<td>high</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Observable LF</td>
<td>not x-shear</td>
<td>yes</td>
<td>modest</td>
<td>low</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Augmented LF</td>
<td>x-shear</td>
<td>yes</td>
<td>modest</td>
<td>high</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>WDF</td>
<td>x-shear</td>
<td>yes</td>
<td>modest</td>
<td>low</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Rihaczek DF</td>
<td>x-shear</td>
<td>yes</td>
<td>better than WDF, not as simple as LF</td>
<td>low</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
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Motivation

• What is the difference between a hologram and a lenticular screen?

• How they capture ‘phase’ of a wavefront for telescope applications?

• What is ‘wavefront coding’ lens for extended depth of field imaging?
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Light Fields

Ramesh Raskar
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