Integration of Cameras in Mobile Phones

- **Units in Millions**
  - Mobile phones
  - Camera phones

- **Years**:

- **Bar Graph**
  - Shows increasing trend from 2000 to 2011 for both mobile phones and camera phones.
  - Mobile phones trend shows a steady increase.
  - Camera phones trend shows a sharp increase from 2005 onwards.
Where are the ‘cameras’?

Image Sensors Markets

Source: Prismark, March 2008
**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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Space of LF representations
Time-frequency representations
Phase space representations
Quasi light field
## Property of the Representation

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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

Reference plane
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
Example: New Representations Augmented Lightfields

rigorous but cumbersome wave optics based

Wigner Distribution Function

ray optics based simple and powerful

limited in diffraction & interference

WDF

Augmented LF

Traditional Light Field

Interference & Diffraction Interaction w/ optical elements

Non-paraxial propagation

Se Baek Oh

3D Optical Systems Group

MIT

CVPR 2009
Introduction to Light Fields

Ramesh Raskar
MIT Media Lab
http://CameraCulture.info
Introduction to Light Fields

- Ray Concepts for 4D and 5D Functions
- Propagation of Light Fields
- Interaction with Occluders
- Fourier Domain Analysis and Relationship to Fourier Optics
- Coded Photography: Modern Methods to Capture Light Field
- Wigner and Ambiguity Function for Light Field in Wave Optics
- New Results in Augmenting Light Fields
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

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

- 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)
Color snapshot

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

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

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

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

Slide by Rick Szeliski and Michael Cohen
- 2D position
- 2D position
- 2 plane parameterization
• 2D position
• 2D position
• 2 plane parameterization
Light Field = Array of (virtual) Cameras

Pixel = (s,t)   Camera = (u,v)
Light Field = Array of (virtual) Cameras
Conventional versus plenoptic camera

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

uv-plane  st-plane
Light Field = Array of (virtual) Cameras
Light Field = Array of (virtual) Cameras
Light Field = Array of (virtual) Cameras

Sub-aperture

Virtual Camera = Sub-aperture View

\[ \sum \]
Computational Photography

Computational Cameras

Generalized Sensor

Processing

Ray Reconstruction

Upto 4D Ray Sampler

Generalized Optics

4D Ray Bender

4D Light Field

Display

Recreate 4D Lightfield

Novel Illumination

Light Sources

Modulators

Generalized Optics

4D Incident Lighting

Scene: 8D Ray Modulator
The light field
[Gershun 1936]

Radiance as a function of position and direction

• for general scenes
  – the “plenoptic function”
  – five-dimensional
  – \( L( x, y, z, \theta, \phi) \) (w/m²sr)

• in free space
  – four-dimensional
  – \( L(u, v, s, t) \)

two-plane parameterization
[Levoy and Hanrahan 1996]
Radiance ‘along a ray’

Radiance $L$ along a ray can be thought of as the amount of light traveling along all possible straight lines through a tube whose size is determined by its solid angle and cross-sectional area.

measured in watts (W) per steradian (sr) per meter squared ($m^2$).
Some alternative parameterizations of the 4D light field, which represents the flow of light through an empty region of three-dimensional space. *Left:* points on a plane or curved surface and directions leaving each point. *Center:* pairs of points on the surface of a sphere. *Right:* pairs of points on two planes in general (meaning any) position.
Light Field Inside a Camera

Subject → Main lens → Photosensor
Light Field Inside a Camera

Lenslet-based Light Field camera

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

Contax medium format camera

Kodak 16-megapixel sensor

Adaptive Optics microlens array

125μ square-sided microlenses

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

[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).

[Diagram of Shack Hartmann wavefront sensor]

- Incoming perturbed wavefronts
- Wavefront tilts over subapertures
- Offset images from subapertures

Measuring shape (phase) of wavefront ~ Lightfield Capture

- [http://www.cvs.rochester.edu/williamslab/r_shackhartmann.html](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.
Example using 45 cameras
[Vaish CVPR 2004]
Synthetic aperture videography
A Virtual Optical Bench

- Understanding rays during defocus
Visualizing Lightfield

(i) Position-angle space  
(ii) Phase-space  
(iii) Space- Spatial Frequency  
(iv) Spectrogram
\[ x_1' = x_1 + \theta_i z \]
flight path through a flatland scene

corresponding looming light field (see also [Hasinoff 2006])
Lego gantry for capturing light fields
(built by Andrew Adams)

- calibration point
- plane + parallax [Vaish 2004]
Light Field = Array of (virtual) Cameras

Sub-aperture

Virtual Camera = Sub-aperture View

Σ
Three ways to capture LF inside a camera

- Shadows using pin-hole array
- Refraction using lenslet array
- Heterodyning using masks
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.
Ives 1933

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 mm' 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
MERL, MIT Media Lab Glare Aware Photography: 4D Ray Sampling for Reducing Glare
Raskar, Agrawal, Wilson & Veeraraghavan
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
Glare = low frequency noise in 2D
• But is high frequency noise in 4D
• Remove via simple outlier rejection
Enhancing Glare

Conventional Photo

Glare Enhanced Image
Glare due to Lens Inter-Reflections
Effects of Glare on Image

- Hard to model, Low Frequency in 2D
- But reflection glare is outlier in 4D ray-space

Lens Inter-reflections

Angular Variation at pixel a
Key Idea

• Lens Glare manifests as low frequency in 2D Image

• But Glare is highly view dependent
  – manifests as outliers in 4D ray-space

• Reducing Glare == Remove outliers among rays
Light Field Inside a Camera

Lenslet-based Light Field camera

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

Contax medium format camera

Kodak 16-megapixel sensor

Adaptive Optics microlens array

125μ square-sided microlenses

4000 × 4000 pixels ÷ 292 × 292 lenses = 14 × 14 pixels per lens
Zooming into the raw photo
Digital Refocusing

Can we achieve this with a Mask alone?

[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

x₀

θ₀

x
Main Lens

Object

1D Sensor

$\theta$

$l(x, \theta)$

$x$

$\theta$-plane

$x$-plane

Line Integral

Captured Photo
Fourier Slice Theorem

Line Integral

Captured Photo

2-D FFT

Central Slice

1-D FFT

FFT of Captured Photo
Light Propagation (Defocus Blur)

\[
L(f_x, f_\theta)
\]

Captured Photo

2-D FFT

1-D FFT

Central Slice

FFT of Captured Photo

\[
f_{\theta}
\]
Extra sensor bandwidth cannot capture extra *angular dimension* of the light field.

Fourier Light Field Space (Wigner Transform)
Sensor Slice captures entire Light Field

Modulated Light Field

Modulation Function
Where to place the Mask?

Mask

Sensor

Mask

Modulation Function

$\mathbf{f}_x$

$\mathbf{f}_\theta$
Computing 4D Light Field

2D Sensor Photo, 1800*1800

2D Fourier Transform, 1800*1800

9*9=81 spectral copies

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

4D Light Field
200*200*9*9
Captured 2D Photo

Image of White Lambertian Plane

Full resolution 2D image of Focused Scene Parts

divide

=
Optical Heterodyning

High Freq Carrier
100.1 MHz

Baseband Audio Signal

99 MHz

Incoming Signal

Reference Carrier

Receiver: Demodulation

Objective Mask Sensor

Software Demodulation

Recovered Light Field

Photographic Signal (Light Field)

Carrier Incident Modulated Signal

Reference Carrier
Light Fields

- What are they?
- What are the properties?
- How to capture?
- What are the applications?
Light Field Applications

• Lens effects
  – Refocussing
  – New aperture setting
  – All in focus image

• Geometric
  – Estimate depth
  – (Create new views)
  – Synthetic aperture (Foreground/background)
  – (Insert objects)

• Statistical
  – Lens glare
  – Specular-diffuse

• Note:
  – LF not required, 4D sampling sufficient
  – Similar HD analysis also works for motion, wavelength, displays
Compound Lens of Dragonfly
“Thin observation module by bound optics (TOMBO),”
J. Tanida, T. Kumagai, K. Yamada, S. Miyatake
Applied Optics, 2001
TOMBO: Thin Camera
\[ x'_1 = x_1 + \theta_i z \]

Shear of Light Field

\[ \text{Shear of Light Field} \]
Light Propagation (Defocus Blur)

\[ L(f_x, f_\theta) \]

2-D FFT

Central Slice

1-D FFT

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Line Integral

\[ l(x, \theta) \]
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- Samples *individual* rays
- Predefined spectrum for lenses
- Chromatic aberration
- High alignment precision
- Peripheral pixels wasted pixels
- Negligible Light Loss
- 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

Other LF representations

Traditional light field

Rihaczek Distribution Function

Observable LF

Augmented LF

Incoherent

Coherent

WDF
Quasi light fields
the utility of light fields, the versatility of Maxwell

We form coherent images by
formulating,
capturing,
and integrating
quasi light fields.
(i) Observable Light Field

- move aperture across plane
- look at directional spread
- continuous form of plenoptic camera

Diagram:
- Scene
- Aperture
- Direction $u$
- Position $s$
(ii) Augmented Light Field with LF Transformer

Interaction at the optical elements
Virtual light projector with real valued (possibly negative radiance) along a ray.

First null (OPD = $\lambda/2$)
(ii) ALF with LF Transformer

- single pinhole
- two pinholes
- rect. aperture
- amplitude grating
- linear phase (prism)
- quadratic phase (lens)
- cubic phase
- phase grating
Tradeoff between cross-interference terms and localization

(i) Spectrogram non-negative localization

(ii) Wigner localization cross terms

(iii) Rihaczek localization complex
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  – George Barbastathis

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