6.098 Digital and Computational Photography
6.882 Advanced Computational Photography

Refoocusing & Light Fields

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Final projects
• Send your slides by noon on Thursday.
• Send final report

Is depth of field a blur?
• Depth of field is NOT a convolution of the image
• The circle of confusion varies with depth
• There are interesting occlusion effects
• (If you really want a convolution, there is one, but in 4D space… more soon)

Wavefront coding
• CDM-Optics, U of Colorado, Boulder
• The worst title ever: "A New Paradigm for Imaging Systems", Cathey and Dowski, Appl. Optics, 2002
• Improve depth of field using weird optics & deconvolution
  • http://www.cdm-optics.com/site/publications.php

Wavefront coding
• Idea: deconvolution to deblur out of focus regions
• Convolution = filter (e.g. blur, sharpen)
• Sometimes, we can cancel a convolution by another convolution
  – Like apply sharpen after blur (kind of)
  – This is called deconvolution
• Best studied in the Fourier domain (of course!)
  – Convolution = multiplication of spectra
  – Deconvolution = multiplication by inverse spectrum
Deconvolution

• Assume we know blurring kernel $k$
  
  $f' = f \ast k$
  
  $\Rightarrow F' = F \ast K$ (in Fourier space)

• Invert by: $F = F' / K$ (in Fourier space)

• Well-known problem with deconvolution:
  – Impossible to invert for $\omega$ where $K(\omega) = 0$
  – Numerically unstable when $K(\omega)$ is small

Wavefront coding

• Idea: deconvolution to deblur out of focus regions

• Problem 1: depth of field blur is not shift-invariant
  – Depends on depth
  
  $\Rightarrow$ If depth of field is not a convolution, it's harder to use deconvolution ;-;

• Problem 2: Depth of field blur "kills information"
  – Fourier transform of blurring kernel has lots of zeros
  – Deconvolution is ill-posed

Ray version

• Idea: deconvolution to deblur out of focus regions

• Problem 1: depth of field blur is not shift-invariant

• Problem 2: Depth of field blur "kills information"

• Solution: change optical system so that
  – Rays don't converge anymore
  – Image blur is the same for all depth
  – Blur spectrum does not have too many zeros

• How it's done
  – Phase plate (wave optics effect, diffraction)
    – Pretty much bends light
    – Will do things similar to spherical aberrations

![Wavefront coding](image1.png)

Fig. 3. PSFs associated with the rays of Fig. 2. The PSFs for a normal system are shown for (A) in focus and (B) out of focus. The PSFs for a coded system are shown in (C) in the normal region of focus and (D) in the out-of-focus region.

![Ray version](image2.png)

Fig. 5. MTFs corresponding with the PSFs of Fig. 3 for a conventional image in and out of focus and a coded image for the same misfocus values.
Other application

- Single-image depth sensing
  - Blur depends A LOT on depth
  - Passive Ranging Through Wave-Front Coding: Information and Application. Johnson, Dowski, Cathey
  - http://graphics.stanford.edu/courses/cs448a-06-winter/johnson-ranging-optics00.pdf

Fig. 9. Example MTF’s for the simulated 1–4m system. The peaks are marked with the range for the simulated MTF.

Single image depth sensing

- Coded imaging
  - What the sensor records is not the image we want, it’s been coded (kind of like in cryptography)
  - Image processing decodes it

Important take-home idea

Other forms of coded imaging

- Tomography
  - e.g. http://en.wikipedia.org/wiki/Computed_axial_tomography
  - Lots of cool Fourier transforms there
- X-ray telescopes & coded aperture
  - e.g. http://universe.gsfc.nasa.gov/casi/coded_intr.html
- Ramesh’s motion blur
- and to some extend, Bayer mosaics

See Berthold Horn’s course

Plenoptic camera refocusing
Plenoptic/light field cameras

- Lipmann 1908
  - "Window to the world"
- Adelson and Wang, 1992
  - Depth computation
- Revisited by Ng et al. for refocusing

The Plenoptic Function

Back to the images that surround us

- How to describe (and capture) all the possible images around us?

The Plenoptic function

- [Adelson & Bergen 91]
- From the greek “total”
- See also

Plenoptic function

- 3D for viewpoint
- 2D for ray direction
- 1D for wavelength
- 1D for time
- can add polarization

Light fields

Fig. 1.3

The plenoptic function describes the information available to an observer at any point in space and time. Always here are two schematic eyes which one should consider to have practiced picking-up gathering parcels of light rays. A real observer cannot see for light rays coming from behind, but the plenoptic function does include these rays.
Idea

- Reduce to outside the convex hull of a scene
- For every line in space
- Store RGB radiance

- Then rendering is just a lookup

- Two major publication in 1996:
  - Light field rendering [Levoy & Hanrahan]
  - The Lumigraph [Gortler et al.]
    - Adds some depth information
    - [http://cs.harvard.edu/~sjg/papers/lumigraph.pdf](http://cs.harvard.edu/~sjg/papers/lumigraph.pdf)

Two-plane parameterization

- Line parameterized by intersection with 2 planes
  - Careful, there are different “isotopes” of such parameterization (slightly different meaning of stuv)

Let’s make life simpler: 2D

- 2-line parameterization

How many dimensions for 3D lines?

- 4: e.g. 2 for direction, 2 for intersection with plane

Let’s make life simpler: 2D

- How many dimensions for 2D lines?
  - Only 2, e.g. y=ax+b <> (a,b)

View?

Figure 1: The light slab representation.
View?

- View ➞ line in Ray space
- Kind of cool: ray ➞ point, and view around point ➞ line
- There is a duality

Back to 3D/4D

Cool visualization

View = 2D plane in 4D

- With various resampling issues

Demo light field viewer
Reconstruction, antialiasing, depth of field

Aperture reconstruction

- So far, we have talked about pinhole view
- Aperture reconstruction: depth of field, better antialiasing

Small aperture

Light field sampling

- Light field spectrum as a function of object distance
  - Slope inversely proportional to depth
  - http://portal.acm.org/citation.cfm?id=344779.344929

Big aperture

[Chai et al. 00, Isaksen et al. 00, Stewart et al. 03]
Light field cameras

Plenoptic camera
- For depth extraction
- Adelson & Wang 92
http://www-bcs.mit.edu/people/jyawang/demos/plenoptic/plenoptic.html

Camera array

Camera arrays

MIT version
- Jason Yang
**Bullet time**

- Time splice http://www.ruffy.com/frameset.htm

**Robotic Camera**

![Image Leonard McMillan](http://www.ruffy.com/frameset.htm)

**Flatbed scanner camera**

- By Jason Yang

**Plenoptic camera refocusing**

**Conventional Photograph**

![Slide by Ren Ng.](http://www.ruffy.com/frameset.htm)

**Light Field Photography**

- Capture the light field inside the camera body
Hand-Held Light Field Camera

Medium format digital camera
Camera in-use
16 megapixel sensor
Micro lens array

Light Field in a Single Exposure

Light Field Inside the Camera Body

Ray carrying $L(u,v,x,y)$

Digital Refocusing

Figure 8: Top: Exploded view of assembly for attaching the microlens array to the digital back. Bottom: Cross-section through assembled parts.
Digital Refocusing

Digitally stopping-down = summing only the central portion of each microlens

Digital Refocusing by Ray-Tracing

Imaginary film

Slide by Ren Ng.
Digital Refocusing by Ray-Tracing

Results of Band-Limited Analysis

• Assume a light field camera with
  – An f/A lens
  – N x N pixels under each microlens

• From its light fields we can
  – Refocus exactly within
    depth of field of an f/(A N) lens

• In our prototype camera
  – Lens is f/4
  – 12 x 12 pixels under each microlens

• Theoretically refocus within
  depth of field of an f/48 lens

Show result video

Automultiscopic displays

3D displays

• With Matthias, Wojciech & Hans
• View-dependent pixels
  – Lenticular optics (microlenses)
Lenticular optics

![Lenticular optics diagram](image)

Figure by Isaksen et al.

Application

- 3D screens are shipping!

![3D screens image](image)

Light Field Microscopy

![Light Field Microscopy](image)

Light field microscopy


![Light field microscopy setup](image)
Conclusions