Refocusing & Light Fields

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Fill the evaluation form
Noise and variance

- Independent random variable X and Y
- denote variance by $\sigma^2$
  (square of the noise level)
- $\sigma^2(X+Y) = \sigma^2(X) + \sigma^2(Y)$ because covariance is zero
- for a scalar a : $\sigma^2(aX) = a^2 \sigma^2(X)$
Multiple-image denoising

- Noisy image $y = x + n$
  where $n$ is additive noise with variance $\sigma^2(n)$
- take 2 images $y_i = x + n_i$
- Denoise by taking their average $0.5(y_1 + y_2)$
- $\sigma^2(0.5(y_1 + y_2)) = 0.25(\sigma^2(n_1) + \sigma^2(n_2)) = 0.5\sigma^2(n)$
- Averaging $N$ images reduces noise by $\sqrt{N}$
Noise model

- For image signal $x$, measured image is $y = x + p + r$
- Photon noise: $\sigma^2(p) \propto x$
- Read noise is completely independent of the signal $\sigma^2(r) =$ constant (depends on sensor and ISO level only)
Subdividing time

- 2 options to take a picture within a time budget:
  - Single exposure $y = x + p + r$
  - Two exposure of half the time: $y_i = 0.5x + p_i + r_i$
    - $\sigma^2(r_i) = \sigma^2(r)$
    - $\sigma^2(p_i) = 0.5 \sigma^2(p)$
  - $y' = y_1 + y_2 = x + r_1 + r_2 + p_1 + p_2$
  - $\sigma^2(y') = \sigma^2(r_1) + \sigma^2(r_2) + \sigma^2(p_1) + \sigma^2(p_2)$
    = $2 \sigma^2(r) + 2 \times 0.5 \sigma^2(p)$
    = $2 \sigma^2(r) + \sigma^2(p)$
  - $y'$ has same photon noise but $\sqrt{2}$ more read noise
Other consequence

- The same is true when creating an image of resolution \( N \times N \) and comparing an \( N \times N \) sensor or a \( 2N \times 2N \) sensor downsampled by a factor of \( 2 \times 2 \).

- Assume the two sensors have the same per-pixel read noise.

- The per-pixel signal is \( 1/4 \) for the high res sensor, and the photon noise is \( 1/2 \)

- The low res image is obtained by adding groups of 4 pixels

- The photon noise level is the same

- The read noise is twice worse
Questions?
Image capture

- A sensor placed alone in the middle of the visual world does not record an image
Image capture

- Pinhole allows you to select light rays
Image formation: optics

- Optics forms an image: selects and integrates light rays
Image formation: computation

- The combination of optics & computation forms the image: selects and combines rays
Computational imaging goals

- Better capture information
- Form image as a post-process

![Diagram showing computational imaging process with stages labeled as Final image, Intermediate optical image, Computation, and Generalized optics.]

Thursday, May 5, 2011
Better capture information

- Same as communication theory: optics encodes, computation decodes
- Code seeks to minimize distortion

Final image

Computation

Intermediate optical image

Generalized optics
Form images as a post-process

- The computational part of formation can be done later and multiple times
- e.g., enable refocusing

The computational part of formation can be done later and multiple times
- e.g., enable refocusing

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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
Back to the images that surround us

• How to describe (and capture) all the possible images around us?
The Plenoptic function

- From the greek "total"
- See also http://www.everything2.com/index.pl?node_id=989303&last_node_id=1102051

Fig. 1.3
The plenoptic function describes the information available to an observer at any point in space and time. Shown here are two schematic eyes-which one should consider to have punctate pupils-gathering pencils of light rays. A real observer cannot see the light rays coming from behind, but the plenoptic function does include these rays.
Plenoptic function

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

*FIGURE 1. The plenoptic function describes all of the image information visible from a particular viewing position.*

From McMillan 95
Light fields
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]
    • http://graphics.stanford.edu/papers/light/
  – The Lumigraph [Gortler et al.]
    • Adds some depth information
    • http://cs.harvard.edu/~sjg/papers/lumigraph.pdf
How many dimensions for 3D lines?

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

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

Figure 1: The light slab representation.
Let's make life simpler: 2D

• How many dimensions for 2D lines?
  – Only 2, e.g. $y=ax+b <> (a,b)$
Let's make life simpler: 2D

- 2-line parameterization
View?
View?

- View $\Rightarrow$ line in Ray space
- Kind of cool: ray $\Rightarrow$ point, and view around point $\Rightarrow$ line
- There is a duality
Back to 3D/4D

From Gortler et al.
Figure 6: Two visualizations of a light field. (a) Each image in the array represents the rays arriving at one point on the uv plane from all points on the st plane, as shown at left. (b) Each image represents the rays leaving one point on the st plane bound for all points on the uv plane. The images in (a) are off-axis (i.e. sheared) perspective views of the scene, while the images in (b) look like reflectance maps. The latter occurs because the object has been placed astride the focal plane, making sets of rays leaving points on the focal plane similar in character to sets of rays leaving points on the object.
Cool visualization

Figure 7: An $(s, u, v)$ slice of a Lumigraph

From Gortler et al.
View = 2D plane in 4D

- With various resampling issues

Figure 12: The process of resampling a light slab during display.
Light field pinhole rendering

• For each pixel x,y in new view
  – consider ray from viewpoint to pixel
  – compute intersection with two planes => s, t, u, v
  – lookup RGB in light field at s, t, u, v

Figure 12: The process of resampling a light slab during display.
Demo light field viewer

- [http://lightfield.stanford.edu/lfs.html](http://lightfield.stanford.edu/lfs.html)
Reconstruction, antialiasing, depth of field
reconstruction challenge

- We rarely have the exact u,v,s,t in the database
- Basic solution: round
- But can lead to aliasing

*Figure 12*: The process of resampling a light slab during display.
4D Interpolation

- point sample
- uv bilerp
- uvst quadlerp
Aperture reconstruction

• So far, we have talked about pinhole view
• Aperture reconstruction
• Each pixel is the integral of rays over an aperture
• Better antialiasing but shallow depth of field
Small aperture
Big aperture

Image Isaksen et al.
Light field sampling

[Chai et al. 00, Isaksen et al. 00, Stewart et al. 03]

- 4D Fourier analysis over light fields
- Light field spectrum as a function of object distance
- Slope inversely proportional to depth

http://graphics.cs.cmu.edu/projects/plenoptic-sampling/ps_projectpage.htm
http://portal.acm.org/citation.cfm?id=344779.344929

From [Chai et al. 2000]
Light field cameras
PHOTOGRAPHIE. — Épreuves réversibles. Photographies intégrales.
Note de M. G. LIPPMANN.

1. La plus parfaite des épreuves photographiques actuelles ne montre que l’un des aspects de la réalité ; elle se réduit à une image unique fixée dans un plan, comme le serait un dessin ou une peinture tracée à la main. La vue directe de la réalité offre, on le sait, infiniment plus de variété. On voit les objets dans l’espace, en vrai grandeur et en relief, et non dans un plan. De plus, leur aspect change avec les positions de l’observateur ; les différents plans de la vue se déplacent alors les uns par rapport aux autres ; la perspective se modifie ; les parties cachées ne restent pas les mêmes ; enfin, si le spectateur regarde le monde extérieur par une fenêtre, il est maître de voir les diverses parties d’un paysage venir s’encadrer successivement entre les bords de l’ouverture, si bien que dans ce cas ce sont des objets différents qui lui apparaissent successivement.

Peut-on demander à la Photographie de nous rendre toute cette variété

Fig. 1.
Plenoptic camera

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

Camera arrays


Figure 2: Our camera tiles contain an Omnivision 8610 image sensor, passive electronics, and a lens mount. The ribbon cables carry video data, synchronization signals, control signals, and power between the tile and the processing board. To keep costs low, we use fixed-focus, fixed-aperture lenses.
Figure 12: Hybrid synthetic aperture photography for combining high depth of field and low motion blur. (a-c) Images captured of a scene simultaneously through three different apertures: a single camera with a long exposure time (a), a large synthetic aperture with short exposure time (b), and a large synthetic aperture with a long exposure time. Computing (a+b-c) yields image (d), which has aliasing artifacts because the synthetic apertures are sampled sparsely from slightly different locations. Masking pixels not in focus in the synthetic aperture images before computing the difference (a + b - c) removes the aliasing (e). For comparison, image (f) shows the image taken with an aperture that is narrow in both space and time. The entire scene is in focus and the fan motion is frozen, but the image is much noisier.
MIT version

- Jason Yang
Bullet time

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

Image Leonard McMillan

Image Levoy et al.
Legos

- [Link](http://lightfield.stanford.edu/aperture.swf?lightfield=data/self_portrait_lf/preview.zip&zoom=1)
Flatbed scanner camera

- By Jason Yang
Plenoptic camera refocusing
Conventional Photograph

Slide by Ren Ng.
Light Field Photography

- Capture the light field inside the camera body
Plenoptic/light field field cameras

- [Lipmann 1908, Adelson and Wang, 1992, Ng et al. 06]
- Record 4D set of rays
  - using microlens array in front of sensor
Hand-Held Light Field Camera

Medium format digital camera

16 megapixel sensor

Camera in-use

Microlens array

Slide by Ren Ng.
Figure 8: Top: Exploded view of assembly for attaching the microlens array to the digital back. Bottom: Cross-section through assembled parts.
Light Field in a Single Exposure
Light Field in a Single Exposure
Light Field Inside the Camera Body

Ray carrying \( L(u, v, x, y) \)
Recap & Questions?

✦ Record 4D set of rays
  • using microlens array in front of sensor
Reconstructing a normal image

- Just integrate all the pixels in an aperture sub-image
Stopping down the lens

- Just integrate the pixels only in the center of an aperture sub-image
Digitally stopping-down

stopping down = summing only the central portion of each microlens
Changing the viewpoint

- Just take one given pixel in each aperture sub-image
  - Viewpoint limited to the lens aperture

**Figure 4**: Two sub-aperture photographs obtained from a light field by extracting the shown pixel under each microlens (depicted on left). Note that the images are not the same, but exhibit vertical parallax.
Digital Refocusing by Ray-Tracing

We have all the light rays
We can generate any virtual view
Digital Refocusing by Ray-Tracing

Lens -> new virtual sensor

original Sensor

Slide by Ren Ng.

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Digital Refocusing by Ray-Tracing

For each pixel of the new view, integrate light rays from different original aperture images.
Digital Refocusing by Ray-Tracing

Lens

Sensor

Imaginary film

Slide by Ren Ng.

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Digital Refocusing by Ray-Tracing

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Web demo

- http://lytro.com/gallery/
Focal stack & plenoptic camera

Light Field Photography with a Hand-Held Plenoptic Camera, Ren Ng, Marc Levoy, Mathieu Brédif, Gene Duval, Mark Horowitz, Pat Hanrahan

- See next time
- Capture light field

- Refocus to create focal stack

- Use photomontage to generate all-focus image
Focal stack & plenoptic camera

Figure 14: Refocusing after a single exposure of the light field camera. Top is the photo that would have resulted from a conventional camera, focused on the clasped fingers. The remaining images are photographs refocused at different depths: middle row is focused on first and second figures; last row is focused on third and last figures. Compare especially middle left and bottom right for full effective depth of field.

Figure 15: Left: Extended depth of field computed from a stack of photographs focused at different depths. Right: A single sub-aperture image, which has equal depth of field but is noisier.

Figure 16: Refocusing of a portrait. Left shows what the conventional photo would have looked like (autofocus mis-focused by only 10 cm on the girl’s hair). Right shows the refocused photograph.

Figure 17: Light field photograph of water splashing out of a broken wine glass, refocused at different depths.

Figure 18: Moving the observer in the macrophotography regime (1:1 magnification), computed after a single light field camera exposure. Top row shows movement of the observer laterally within the lens plane, to produce changes in parallax. Bottom row illustrates changes in perspective by moving along the optical axis, away from the scene to produce a near-orthographic rendering (left) and towards the scene to produce a medium wide angle (right). In the bottom row, missing rays were filled with closest available (see Figure 7).

From Ng et al. http://graphics.stanford.edu/papers/lfcamera/
Refocus range analysis


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

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

• In prototype camera
  – Lens is $f/4$
  – $12 \times 12$ pixels under each microlens

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

Slide by Ren Ng.

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Show result

- http://lytro.com/about/index.html
Automultiscopics displays
3D displays

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

Figure by Isaksen et al.
Application

• 3D screens are shipping!
Light Field Microscopy
Light field microscopy

Figure 2: Optical layout of our light field microscope. (a) In a transmission-mode light microscope, an illumination source is focused by a condenser lens at A onto a specimen at B. An objective lens at C magnifies the specimen, creating a real image at intermediate image plane D. In older microscopes, this plane is located inside the microscope tube. An ocular (eyepiece) at E further magnifies the central portion of this image, creating a second image focused at infinity. (b) In our design the ocular is removed, a microlens array F is placed at the intermediate image plane, and a camera sensor is placed behind this at G, positioned so that each microlens records an in-focus image of the objective (green rays). In light field parallax, if the objective aperture and specimen constitute the uv and st planes, then the camera sensor and microlens array constitute a reimagining of these two planes. This drawing is not to scale; typical distances are shown beside it. (c) Our prototype consists of a Nikon Optiphot and custom microlens array (red circle). To avoid building a special camera, we re-image G using a Canon 5D 35mm SLR with a 1:1 macro lens.
Figure 1: At left is a light field captured by photographing a speck of fluorescent crayon wax through a microscope objective and microlens array. The objective magnification is 16x, and the field of view is 1.3mm wide. The image consists of $170^2$ subimages, one per microlens, each depicting a different part of the specimen. An individual subimage contains $20^2$ pixels, each representing a different point on the objective lens and hence a unique direction of view. By extracting one pixel from each subimage, we can produce perspective views of the specimen, a sequence of which is shown at top-right. Alternatively, by summing the pixels in each subimage, we can produce orthographic views with a shallow depth of field, like an ordinary microscope but of lower spatial resolution. Shearing the light field before summing, we can focus at different depths, as shown in the sequence at bottom-right. These images were computed in real-time on a PC.
Conclusions
Computational imaging goals

- Better capture information
- Form image as a post-process

Diagram showing steps:
- Computation
- Intermediate optical image
- Final image
- Generalized optics
Computational Photography

Novel Cameras

- Generalized Sensor
- Processing
- Generalized Optics
- Upto 4D Ray Sampler
- 4D Ray Bender
- 4D Ray Modulator
- 4D Illumination field + Time + Wavelength
- Programmable

Scene: 8D Ray Modulator

Light Sources

Display

Recreate 4D

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