Improving Film-Like Photography

aka,

Epsilon Photography

Ankit Mohan

 Courtesy of Ankit Mohan. Used with permission.
‘Pinhole’ Model: Rays copy scene onto ‘film’

Film-like Optics: Imaging Intuition

Well-Lit 3D Scene: Angle($\theta, \phi$)

Ray

‘Center of Projection’

Position (x, y)

2D Sensor: Pixel Grid or Film,…

‘Pinhole’ Model: Rays copy scene onto ‘film’
Film-like Optics: Imaging Intuition

‘Pinhole’ Model: Rays copy scene onto ‘film’
Not One Ray, but a Bundle of Rays

Scene

Angle(θ, φ)

Ray

Lens

Sensor

Position (x, y)

‘Center of Projection’
• (BUT Ray model *isn’t perfect*: ignores diffraction)

• Lens, aperture, and diffraction sets the point-spread-function (PSF)

How do we compute $S_1$ and $S_2$ for a lens?

What is the ‘Ray-Bending Strength’ for a lens?
• Lens focal length $f$: where parallel rays converge

\[
S_1 = \infty \quad S_2 = f
\]
Review: Focal Length $f$

- Lens focal length $f$: where parallel rays converge
- **smaller** focal length: **more** ray-bending ability…

$S_1 = \infty$
Lens focal length $f$: where parallel rays converge

- greater focal length: less ray-bending ability...
- For flat glass; for air: $f = \infty$
Review: Thin Lens Law

• Thin Lens Law: in focus when:

\[
\frac{1}{S_1} + \frac{1}{S_2} = \frac{1}{f}
\]

• Note that \( S_1 \geq f \) and \( S_2 \geq f \)

Try it Live! Physlets…

http://webphysics.davidson.edu/Applets/Optics/intro.html
Aperture and Depth-Of-Focus:

For same focal length:
- Smaller Aperture $\rightarrow$ Larger focus depth, but less light
Aperture and Depth-Of-Focus:

For same focal length:
• Larger Aperture $\rightarrow$ smaller focus depth, but more light.
Auto-Focus

• Phase based autofocus: Used in most SLR cameras.

• Contrast based autofocus: Maximize image contrast in AF region; used in most digital compact cameras.

• Active autofocus: Ultrasonic and IR based; used in compact film cameras.
Problem: Map Scene to Display

Domain of Human Vision:
from $\sim 10^{-6}$ to $\sim 10^8$ cd/m²

Range of Typical Displays:
from $\sim 1$ to $\sim 100$ cd/m²
Dynamic Range Limits

Under-Exposure
• Highlight details: Captured
• Shadow details: Lost

Over-Exposure
• Highlight details: Lost
• Shadow details: Captured
The Media Lab | Camera Culture

- Shutter Speed
- Exposure
- Aperture size
- Film Sensitivity (ISO)
- Linear Relationship

Linear Relationship
Auto-Exposure
[Nikon Matrix Metering]

Images removed due to copyright restrictions.
Scanned product technical literature, similar to that presented at
Color sensing in Digital Cameras

Bayer filter pattern

Foveon X3 sensor

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Electromagnetic spectrum

Visible Light: ~400-700 nm wavelength

Source: NASA
Three color primaries

sRGB color space

Fuji Velvia 50 film

Nikon D70 camera
Epsilon Photography

Capture multiple photos, each with slightly different camera parameters.

- Exposure settings
- Spectrum/color settings
- Focus settings
- Camera position
- Scene illumination
Epsilon Photography

- epsilon over time (bracketing)
- epsilon over sensors (3CCD, SAMP, camera arrays)
- epsilon over pixels (bayer)
- epsilon over multiple axes
Epsilon over time (Bracketing)

Capture a sequence of images (over time) with epsilon change in parameters
High Dynamic Range (HDR) capture

- negative film = 250:1 (8 stops)
- paper prints = 50:1
- [Debevec97] = 250,000:1 (18 stops)
- Old idea; [Mann & Picard 1990]
  hot topic at recent SIGGRAPHs

Images removed due to copyright restrictions.
Memorial Church photo sequence from Paul Debevec,
“Recovering High Dynamic Range Radiance Maps from Photographs.”
(SIGGRAPH 1997)
Epsilon over time (Bracketing)

Epsilon over \text{time} \ (\text{Bracketing})

Image courtesy of shannonpatrick17 on Flickr.

Color wheel used in DLP projectors
Epsilon over sensors

Capture a set of images (over different sensors or cameras) with epsilon change in parameters
Epsilon over sensors

3CCD imaging system for color capture
Epsilon over sensors

Single-Axis Multi-Parameter (SAMP) Camera

[McGuire et al, 2005]

Multiple cameras at the same virtual position

Images removed due to copyright restrictions.
Epsilon over sensors

Camera Arrays

Epsilon over camera position

64 tightly packed commodity CMOS webcams, 30 Hz, scalable, real-time

Epsilon over sensors

Stanford Camera Array [Wilburn et al, SIGGRAPH 2005]

Photo of camera array removed due to copyright restrictions.
See “High Performance Imaging Using Large Camera Arrays.”
Epsilon over pixels

Capture images (over different pixels on the same sensor) with epsilon change in parameters
Epsilon over pixels

Bayer Mosaicing for color capture

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Estimate RGB at ‘G’ cells from neighboring values
Epsilon over multiple axes

Image removed due to copyright restrictions.
Generalized Mosaicing
[Schechner and Nayar, ICCV 2001]
HDR From Multiple Measurements

Captured Images

Computed Image


Ginosar et al 92, Burt & Kolczynski 93, Madden 93, Tsai 94, Saito 95, Mann & Picard 95,Debevec & Malik 97, Mitsunaga & Nayar 99,Robertson et al. 99, Kang et al. 03

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Sequential Exposure Change:

Ginosar et al 92, Burt & Kolczynski 93, Madden 93, Tsai 94, Saito 95, Mann 95, Debevec & Malik 97, Mitsunaga & Nayar 99, Robertson et al. 99, Kang et al. 03

Mosaicing with Spatially Varying Filter:

(Pan or move the camera)

Schechner and Nayar 01, Aggarwal and Ahuja 01

Multiple Image Detectors:

Doi et al. 86, Saito 95, Saito 96, Kimura 98, Ikeda 98, Aggarwal & Ahuja 01, …
**Multiple Sensor Elements in a Pixel:**

Handy 86, Wen 89, Murakoshi 94, Konishi et al. 95, Hamazaki 96, Street 98

**Assorted Pixels:**

Generalized Bayer Grid:
Trade resolution for multiple exposure, color

Nayar and Mitsunaga 00, Nayar and Narasimhan 02

**Computational Pixels:**

(pixel sensitivity set by its illumination)

Brajovic & Kanade 96, Ginosar & Gnusin 97, Serafini & Sodini 00
### Assorted Pixels [Nayar and Narsihman 03]

The Bayer Grid Interleaved color filters.

Let's interleave OTHER assorted measures too.

‘De-mosaicking’ helps preserve resolution…

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Assorted Pixels [Nayar and Narsihman 03]
The Media Lab  \hspace{0.09em} |  \hspace{0.09em} Camera Culture

**LCD Adaptive Light Attenuator**  
[Nayar and Branzoi, ICCV 2003]

LCD Light Attenuator limits image intensity reaching 8-bit sensor

Unprotected 8-bit Sensor Output:

Attenuator-Protected 8-bit Sensor Output

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High Dynamic Range (HDR) display

[Seetzen, Heidrich, et al, SIGGRAPH 2004]

Image removed due to copyright restrictions.
Schematic of HDR display with projector, LCD and optics; and photo of the working display.
See Figure 4 in Seetzen, H., et al. “High Dynamic Range Display Systems.”

http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.128.1621&rep=rep1&type=pdf
Focus: extending the depth of field

- Focal stacks - used in microscopy
- Light field cameras
Several slides removed due to copyright restrictions.
Sequence of photos of insect head, with progression of different focal points.
See “Extended depth-of-field” example at:
Focus: Light field camera

Light field
↓
focal stack
↓
extended DOF

Courtesy of Ren Ng. Used with permission.
Focus: shallow depth of field

Lots of glass; Heavy; Bulky; Expensive

Example photos removed due to copyright restrictions.
Defocus Magnification
[Bae and Durand 2007]

Images removed due to copyright restrictions.
See Figure 1 in Bae, S., and F. Durand. "Defocus Magnification."
Synthetic aperture photography

Huge lens' ray bundle is now summed COMPUTATIONALLY:
Synthetic aperture photography

Computed image:
large lens’ ray bundle
Summed for each pixel
Synthetic aperture photography

“Impossibly Large” lens:

Lens gathers a bundle of rays for each image point...

Camera array gathers and sums the same sets of rays
Synthetic aperture photography

Camera array is far away from these bushes, yet it sees...

Focus Adjustment: Sum of Bundles

[Vaish et al. 2004]

Uncalibrated Synthetic Aperture
[Kusumoto, Hiura, Sato, CVPR 2009]

photos taken from any view points

defocus controlled images

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Uncalibrated Synthetic Aperture

[Kusumoto, Hiura, Sato, CVPR 2009]

Focus in front

Focus in back

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Image Destabilization

[Mohan, Lanman et al. 2009]
Image Destabilization

[Mohan, Lanman et al. 2009]
Lens based Focusing

Diagram showing the lens-based focusing mechanism with points A and B mapping to A' and B' respectively.
Lens based Focusing

A

Lens

B

Sensor

A'

B'
Smaller aperture $\rightarrow$ Smaller defocus blur
Pinhole: All In-Focus
Shifting Pinhole

Pinhole

Sensor

$A$

$B$

$A'$

$B'$

$v_p$
Shifting Pinhole
Shifting Pinhole

Pinhole

Sensor

$A'$

$B'$

$A$

$B$

$v_p$
Shifting Pinhole

Pinhole

Sensor

$A$

$B$

$A'$

$B'$

$v_p$
Shifting Pinhole

\[ B \rightarrow A \rightarrow \text{Pinhole} \rightarrow \text{Sensor} \]

- \( d_a \)
- \( d_b \)
- \( d_s \)
- \( v_p \)
- \( t_p \)
- \( A' \)
- \( B' \)

\[ (1 + \frac{d_s}{d_b}) t_p \]

\[ (1 + \frac{d_s}{d_a}) t_p \]
Shifting Pinhole and Sensor

\[ v_s = \left(1 + \frac{d_s}{d_a}\right)v_p \]

Focus Here
Shifting Pinhole and Sensor

\[ v_s = \left(1 + \frac{d_s}{d_a}\right) v_p \]

Focus Here
Shifting Pinhole and Sensor

\[ v_s = \left(1 + \frac{d_s}{d_a}\right)v_p \]
Shifting Pinhole and Sensor

\[ v_s = \left( 1 + \frac{d_s}{d_b} \right) v_p \]
A Lens in Time!

Lens Equation: \[
\frac{1}{f_P} = \frac{1}{u} + \frac{1}{v}
\]

Virtual Focal Length: \[ f_P = \left( \frac{v_p}{v_s} \right) d_s \]

Virtual F-Number: \[ N_P = \left( \frac{v_p}{v_s} \right) \left( \frac{d_s}{t_p} \right) \]

Analogous to *shift and sum* based Light field re-focusing.
Our Prototype
Adjusting the Focus Plane

all-in-focus pinhole image

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Defocus Exaggeration

destabilization simulates a reduced f-number

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Large apertures with tiny lenses?

**Benefits**
- No *time* or *light* inefficiency wrt cheap cameras
- Exploits unused area around the lens
- Compact design
- With near-pinhole apertures (*mobile phones*) many possibilities

**Limitations**
- Coordinated mechanical movement required
- Diffraction (due to small aperture) cannot be eliminated
  - [Zhang and Levoy, tomorrow]
  - [Our group: augmented LF for wave analysis]
- Scene motion during exposure

Photo courtesy of Wikipedia User: Lipton_sale.

Figure by MIT OpenCourseWare.
Increasing Spatial Resolution

- Superresolution
- Panoramas over time
- Panoramas over sensors
Capturing Gigapixel Images
[Kopf et al, SIGGRAPH 2007]

Image removed due to copyright restrictions.
See Fig. 4b in Kopf, J., et al. "Capturing and Viewing Gigapixel Images."

3,600,000,000 Pixels
Created from about 800 8 MegaPixel Images
Capturing Gigapixel Images
[Kopf et al, 2007]

Image removed due to copyright restrictions.

“Normal” perspective projections cause distortions.
Capturing Gigapixel Images
[Kopf et al, 2007]

Image removed due to copyright restrictions.
See Fig. 4b in Kopf, J., et al. “Capturing and Viewing Gigapixel Images.”

100X variation in Radiance

High Dynamic Range
A tiled camera array

- 12 x 8 array of VGA cameras
- abutted: 7680 x 3840 pixels
- overlapped 50%: half of this
- total field of view = 29° wide
- (seamless mosaicing isn’t hard)
- cameras individually metered
- Approx same center-of-proj.

Photo removed due to copyright restrictions. See
(Figure 1a in Wilburn, B., et al. SIGGRAPH 2005)
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Tiled panoramic image
(before geometric or color calibration)

Photo removed due to copyright restrictions.
Tiled panoramic image
(after geometric or color calibration)

Photo removed due to copyright restrictions.
Three images removed due to copyright restrictions.
Similar to Fig. 6 and 7 in Wilburn, B., et al. “High Performance Imaging Using Large Camera Arrays.” Proceedings of SIGGRAPH 2005.
Increasing Temporal Resolution

Say you want 120 frame per second (fps) video.
• You could get one camera that runs at 120 fps
• Or…
Increasing Temporal Resolution

Say you want 120 frame per second (fps) video.
• You could get one camera that runs at 120 fps
• Or… get 4 cameras running at 30 fps.
Increasing Temporal Resolution

High Speed Video Using a Dense Camera Array [Wilburn et al, CVPR 2004]

1560fps video of popping balloon

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Epsilon Photography

Modify …

- Exposure settings
- Spectrum/color settings
- Focus settings
- Camera position
- Scene illumination

… over …

- time (bracketing)
- sensors (SAMP, camera arrays)
- pixels (bayer)