Image Formation and Optics

Acknowledgement: many slides by S. Rusinkiewicz
Image Formation + Capture

- Devices
- Sources of Error
Optics

- Lenses
- Focus, aperture, distortion
Pinhole Camera

- “Camera obscura”

Object → Pinhole → Image plane → Image
Pinhole Camera

- Aperture too big: blurry image
- Aperture too small:
  requires long exposure or high intensity
- Aperture much too small:
  diffraction through pinhole $\Rightarrow$ blurry image

- Rule of thumb: aperture should be significantly larger than wavelength of light
  (400-700 nm)
Lenses

- Focus a bundle of rays from a scene point onto single point on the imager
- Result: can make aperture larger
Ideal “Thin” Lens Law

• Relationship between focal length and focal distance:

\[ \frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f} \]
Camera Adjustments

- Focus?
- Iris?
- Zoom?
Focus and Depth of Field

• For a given $d$, “perfect” focus at only one $d_0$

• In practice, OK for some range of depths
  • Circle of confusion smaller than a pixel

• Better depth of field with smaller aperture, but requires more light intensity (closer to pinhole camera)
Field of View

Q: What does field of view of camera depend on?
- Focal length of lens
- Size of imager
- Object distance?

\[ \theta = 2 \tan^{-1} \frac{x_i}{2f} \]
\[ \theta \approx \frac{x_i}{f} \]
Aperture

• Controls amount of light
• Affects depth of field
• Affects distortion (thin-lens approximation is better near center of lens)
Aperture

• Aperture typically given as “f-number”
• What is f/4?
  • Aperture diameter is $\frac{1}{4}$ the focal length
• One “f-stop” equals change of f-number by $\sqrt{2}$
  • Equals change in aperture area by factor of 2
  • Equals change in amount of light by factor of 2
• Example: f/2 $\rightarrow$ f/2.8 $\rightarrow$ f/4
Charge Coupled Devices

Acknowledgment: Michael Richmond
Charge Coupled Devices

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CCD Read-Out

Acknowledgment: Michael Richmond
CCD Noise

- Thermal ("dark current") noise:
  - Thermal energy generates electrons in silicon chip (indistinguishable from electrons generated by photons)

- Read-out noise:
  - Noise in digitization process
Capturing Color
Capturing Color
Capturing Color
Errors in Digital Images
Sources of Error

• Geometric (focus, distortion)
• Color (spectral aliasing, chromatic aberration)
• Radiometric (vignetting)
• Bright areas (flare, bloom, clamping)
• Signal processing (gamma, compression)
• Noise
Monochromatic Aberrations

• Real lenses do not follow ideal thin lens approximation

• Only valid if \( \sin(\theta) \sim \theta \)
Spherical Aberration

- Results in blurring of image, focus shifts when aperture is adjusted.
- Exact distortion depends on orientation of lens.
Radial Distortion

- Varies with placement of aperture
Radial Distortion
Chromatic Aberration

- Due to dispersion in glass (focal length varies with wavelength of light)
- Result: color fringes
- Worst at edges of image
- Correct with lens system with multiple types of glass
Correcting for Aberrations

- Compound lenses use multiple lens elements to "cancel out" distortion and aberration
Vignetting

- Darkening of image toward edges
- Optical: less power per unit area transferred for light at an oblique angle
- Mechanical: due to apertures
Vignetting

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Vignetting

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Lens Flare

- Light reflecting from glass-air interfaces
- Results in ghost images or haziness
- Worse in multi-lens systems
- Ameliorated by optical coatings
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Bloom

- Overflow charge in pixel “buckets”
- Spills into neighboring pixels
- Streaks (usually vertical) next to bright areas
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Dynamic Range

- Most consumer digital cameras have 8-bit (per color channel) dynamic range
  - Can be non-linear: more than 255:1 intensity range
  - Too bright: clamp to 255
  - Too dim: clamp to 0
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High Dynamic Range

- Extend dynamic range with multiple exposures [Debeved and Malik 97]
- Sean Arietta will present this topic next.
Noise
Noise
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Noise

- Thermal noise: in all electronics
  - Noise at all frequencies
  - Proportional to temperature
- Shot noise: quantum effect related to discrete energy levels
  - Shows up at extremely low light intensities
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- Shot noise: quantum effect related to discrete energy levels
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Noise

- $1/f$ noise ("pink noise") - inversely proportional to frequency
  - Not completely understood
  - Can be dominant source of noise
  - All of the above apply for imager and amplifier
Filtering Noise

• Low-pass filter (e.g. Gaussian)
• Edge-preserving adaptive filters (e.g. bilateral filter)
• “Despeckling” uses a median filter to remove dead pixels
Lenses

- Focus a bundle of rays from a scene point onto single point on the imager
What do lenses see?

Surface

Lens

Image Plane (film, CCD)
What do lenses see?

\[ I = L A_{surf} \]

\[ \Phi = L A_{surf} \frac{A_{aperture}}{d_{surf}^2} \]
What do lenses see?

$\Phi = LA_{surf} \frac{A_{aperture}}{d_{surf}^2}$

Area $A_{surf}$
Radiance $L$

$I = LA_{surf}$
What do lenses see?

\[ I = L A_{surf} \]

\[ \Phi = L A_{surf} \frac{A_{aperture}}{d^2_{surf}} \]

\[ E = \frac{\Phi}{A_{img}} \]
What do lenses see?

\[ d_{surf} \quad d_{img} \]

Area \( A_{surf} \)
Radiance \( L \)
\[ I = L A_{surf} \]

Area \( A_{aperture} \)
\[ \Phi = L A_{surf} \frac{A_{aperture}}{d_{surf}^2} \]

Area \( A_{img} \)
\[ E = \frac{\Phi}{A_{img}} \]
What do lenses see?

\[ I = L A_{\text{surf}} \]
\[ \Phi = L A_{\text{surf}} \frac{A_{\text{aperture}}}{d_{\text{surf}}^2} \]
\[ E = \frac{\Phi}{A_{\text{img}}} \]

\[ E \propto L \frac{A_{\text{aperture}} A_{\text{surf}}}{d_{\text{surf}}^2 A_{\text{img}}} \]
\[ \frac{A_{\text{surf}}}{A_{\text{img}}} = \frac{d_{\text{surf}}^2}{d_{\text{img}}^2} \]
\[ E = L \frac{A_{\text{aperture}}}{d_{\text{img}}^2} \]

Punchline:
“Cameras see radiance”