Announcements

- Assignment 1 Posted to the web page: Due Thursday, 10/21/10
- Additional TA office hour - To be announced
- Read Chapter 4 of Forsyth & Ponce
- Textbook warning: Last year, some students have used an online version of the text. I believe that it’s a draft version and it doesn’t include chapters 2 & 3

Last lecture in a nutshell

Thin Lens: Image of Point

\[
\frac{1}{z'} - \frac{1}{z} = \frac{1}{f}
\]

Deviations from the lens model

Deviations from this ideal are **aberrations**

Two types

1. geometrical
   - spherical aberration
   - astigmatism
   - distortion
   - coma

2. chromatic

Aberrations are reduced by combining lenses, coatings

Spherical aberration

Rays parallel to the axis do not converge

Outer portions of the lens yield smaller focal lengths
Radiometry

Read Chapter 4 of Ponce & Forsyth

• Solid Angle
• Irradiance
• Radiance
• BRDF
• Lambertian/Phong BRDF

Solid Angle

• By analogy with angle (in radians), the solid angle subtended by a region at a point is the area projected on a unit sphere centered at that point.
• The solid angle subtended by a patch area $dA$ is given by

$$do = \frac{dA \cos \theta}{r^2}$$

Radiance

• Power is energy per unit time
• Radiance: Power traveling at some point in a specified direction, per unit area perpendicular to the direction of travel, per unit solid angle
• Symbol: $L(x, \theta, \phi)$
• Units: watts per square meter per steradian; w/(m²sr)

$$L = \frac{P}{(dA \cos \alpha) do}$$

Power emitted from patch, but radiance in direction different from surface normal.

Irradiance

• How much light is arriving at a surface?
• Units of irradiance: Watts/m²
• This is a function of incoming angle.
• A surface experiencing radiance $L(x, \theta, \phi)$ coming in from solid angle $do$ experiences irradiance:

$$E(x) = L(x, \theta, \phi) \cos \theta do$$

Crucial property: Total irradiance arriving at the surface is given by adding irradiance over all incoming angles.

Total irradiance $E$ is:

$$E = \int L(x, \theta, \phi) \cos \theta \sin \theta d\phi d\theta$$

Radiometry of thin lenses

What is image irradiance $E$ for a radiance $L$ emitted from a point $P$?
Let $\delta \omega$ be the solid angle subtended by $\delta A$ (or $\delta A'$) from the center of the lens:

$$\delta \omega = \frac{\delta A \cos \alpha}{G \cos \beta}.$$

$$= \frac{\delta A \cos \alpha}{G \cos \beta}, \quad \delta A \cos \alpha.$$  

The power $\delta P$ emitted from the patch $\delta A$ with radiance $L$ and falling on the lens is:

$$\delta P = \delta A L \cos \alpha \cos \beta.$$  

And the irradiance $\delta P/\delta A'$ is:

$$E = \frac{\delta P}{\delta A'} = \frac{\delta A L \cos \alpha \cos \beta}{\delta A'}.$$  

Camera’s sensor

- Measured pixel intensity is a function of irradiance integrated over:
  - pixel’s area
  - over a range of wavelengths
  - for some period of time

$$I = \int_{x} \int_{y} \int_{\lambda} \int_{t} E(x, y, \lambda, t) s(x, y) q(\lambda) dy dx dt$$

- Ideally, it’s linear to the radiance, but the camera response $C(.)$ may not be linear

$$I = C \left( \int_{x} \int_{y} \int_{\lambda} \int_{t} E(x, y, \lambda, t) s(x, y) q(\lambda) dy dx dt \right)$$

Image sensor

Two types:

1. CCD
2. CMOS
CCD
separate photo sensor at regular positions
no scanning
charge-coupled devices (CCDs)
interline transfer and frame transfer
photosensitive storage

CCD vs. CMOS
• Mature technology
• Specific technology
• High production cost
• High power consumption
• Higher fill rate
• Blooming
• Sequential readout

• Mature technology
• Standard IC technology
• Cheap
• Low power
• Less sensitive
• Per pixel amplification
• Random pixel access
• Smart pixels
• On chip integration
  with other components

CMOS
Each photo sensor has its own amplifier
More noise (reduced by subtracting ‘black’ image)
Lower sensitivity (lower fill rate)
Uses standard CMOS technology
Allows to put other components on chip
‘Smart’ pixels

Color Cameras
We consider 3 concepts:
1. Prism (with 3 sensors)
2. Filter mosaic
3. Filter wheel
   … and X3

Prism color camera
Separate light in 3 beams using dichroic prism
Requires 3 sensors & precise alignment
Good color separation

Filter mosaic
Coat filter directly on sensor
demosaicing (obtain full colour & full resolution image)
Filter wheel
Rotates multiple filters in front of lens
Allows more than 3 colour bands

Only suitable for static scenes

Prism vs. mosaic vs. wheel

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<th>approach</th>
<th>Prism</th>
<th>Mosaic</th>
<th>Wheel</th>
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<td>Separation</td>
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<td>Average</td>
<td>Good</td>
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<td>Alasing</td>
<td>Motion</td>
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<td>Bands</td>
<td>3</td>
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High-end cameras | Low-end cameras | Scientific applications

“newer” color CMOS sensor
Foveon’s X3

Better image quality
Smarter pixels

Light at surfaces

Many effects when light strikes a surface -- could be:
- transmitted
  - Skin, glass
- reflected
  - mirror
- scattered
  - milk
- travel along the surface and leave at some other point
- absorbed
  - sweaty skin

Assume that
- surfaces don’t fluoresce
  - e.g. scorpions, detergents
- surfaces don’t emit light (i.e. are cool)
- all the light leaving a point is due to that arriving at that point

BRDF

With assumptions in previous slide:
- Bi-directional Reflectance Distribution Function $P(\theta_{in}, \phi_{in}; \theta_{out}, \phi_{out})$
- Ratio of emitted radiance to incident irradiance (units: m$^{-2}$)
- Function of:
  - Incoming light direction: $\theta_{in}, \phi_{in}$
  - Outgoing light direction: $\theta_{out}, \phi_{out}$

\[
\rho(\xi, \theta_{in}, \phi_{in}; \theta_{out}, \phi_{out}) = \frac{L_{e}(\xi, \theta_{in}, \phi_{in})}{L_{i}(\xi, \theta_{out}, \phi_{out}) \cos \theta_{out}}
\]

Where $\rho$ is sometimes denoted $f_r$

The Reflection Equation

Emitted radiance in direction $f_r$ for incident radiance $L_i$

\[
L_i(x, \omega_i) = \int_{\omega_i} f_r(x, \omega_i \rightarrow \omega_i) L_i(x, \omega_i) \cos \theta_i \, d\omega_i
\]

where $\omega_i = (\theta_i, \phi_i)$
Properties of BRDFs

1. Non-negative: \( \rho(\theta_{\text{in}}, \phi_{\text{in}}; \theta_{\text{out}}, \phi_{\text{out}}) \geq 0 \)

2. Helmholtz Reciprocity Principle:
   \( \rho(\theta_{\text{in}}, \phi_{\text{in}}; \theta_{\text{out}}, \phi_{\text{out}}) = \rho(\theta_{\text{out}}, \phi_{\text{out}}; \theta_{\text{in}}, \phi_{\text{in}}) \)

3. Total energy leaving a surface must be less than total energy arriving at the surface

\[
\int f_x(x,\theta,\phi) \cos \theta \, dx \leq \int \int \int \rho(\theta',\phi';\theta,\phi) \times f_x(x,\theta,\phi) \cos \theta' \, dx' \, d\theta' \, d\phi'
\]

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Surface Reflectance Models

**Common Models**

- Lambertian
- Phong
- Physics-based
  - Specular
  - [Shin 1977], [Cook-Torrance 1982], [Ward 1992]
  - Diffuse
  - [Hanrahan, Kender 1993]
  - Generalized Lambertian
  - [Atten, Nayar 1993]
  - Thoroughly Pitted Surfaces
  - [Koenderink et al 1999]
- Phenomenological
  - [Koenderink, Van Doorn 1996]

**Arbitrary Reflectance**

- Non-parametric model
- Anisotropic
- Non-uniform over surface
- BRDF Measurement
  - [Dana et al, 1999], [Marschner]