Basic Principles of Imaging and Photometry

Lecture #2

Thanks to Shree Nayar, Ravi Ramamoorthi, Pat Hanrahan
We need to understand the Geometric and Radiometric relations between the scene and its image.
A Brief History of Images

Camera Obscura, Gemma Frisius, 1558
A Brief History of Images

Lens Based Camera Obscura, 1568
A Brief History of Images

Still Life, Louis Jaques Mande Daguerre, 1837
A Brief History of Images

Silicon Image Detector, 1970
A Brief History of Images

Digital Cameras
1.3 billion

120 million
TOPICS TO BE COVERED:

1) Pinhole and Perspective Projection
2) Image Formation using Lenses
3) Lens related issues
Pinhole and the Perspective Projection

Is an image being formed on the screen?

YES! But, not a “clear” one.

\[
\frac{r'}{f'} = \frac{r}{z} \quad \Rightarrow \quad \frac{x'}{f'} = \frac{x}{z} \quad \frac{y'}{f'} = \frac{y}{z}
\]
Magnification

From perspective projection:

\[
\frac{x'}{f'} = \frac{x}{z} \quad \frac{y'}{f'} = \frac{y}{z}
\]

\[
\frac{x' + \delta x'}{f'} = \frac{x + \delta x}{z} \quad \frac{y' + \delta y'}{f'} = \frac{y + \delta y}{z}
\]

Magnification:

\[
m = \frac{d'}{d} = \frac{\sqrt{(\delta x')^2 + (\delta y')^2}}{\sqrt{\delta x^2 + \delta y^2}} = \frac{f'}{z}
\]

\[
\frac{\text{Area}_{\text{image}}}{\text{Area}_{\text{scene}}} = m^2
\]
Orthographic Projection

Magnification: \( x' = m \ x \quad y' = m \ y \)

When \( m = 1 \), we have orthographic projection.

This is possible only when \( z \gg \Delta z \)
In other words, the range of scene depths is assumed to be much smaller than the average scene depth.
Problems with Pinholes

- Pinhole size (aperture) must be “very small” to obtain a clear image.

- However, as pinhole size is made smaller, less light is received by image plane.

- If pinhole is comparable to wavelength of incoming light, DIFFRACTION effects blur the image!

- Sharpest image is obtained when:

  \[
  d = 2 \sqrt{f' \lambda}
  \]

  Example: If \( f' = 50\text{mm} \),
  \[\lambda = 600\text{nm (red)},\]
  \[d = 0.36\text{mm}\]
Image Formation using Lenses

- Lenses are used to avoid problems with pinholes.
- Ideal Lens: Same projection as pinhole but gathers more light!

Gaussian Lens Formula: \( \frac{1}{i} + \frac{1}{o} = \frac{1}{f} \)

- \( f \) is the focal length of the lens – determines the lens’s ability to bend (refract) light
- \( f \) different from the effective focal length \( f' \) discussed before!
**Focus and Defocus**

**Depth of Field:** Range of object distances over which image is **sufficiently well** focused. i.e. Range for which *blur circle* is less than the resolution of the imaging sensor.

**Blur Circle Diameter:**

\[
 b = \frac{d}{i'} (i' - i)
\]
Two Lens System

- Rule: Image formed by first lens is the object for the second lens.

- Main Rays: Ray passing through focus emerges parallel to optical axis. Ray through optical center passes un-deviated.

- Magnification: \[ m = \frac{i_2}{i_1} \cdot \frac{o_1}{o_2} \]

Exercises: What is the combined focal length of the system? What is the combined focal length if \( d = 0 \)?
Lens related issues

**Compound (Thick) Lens**
- Principal planes
- Nodal points
- Thickness

**Vignetting**
- More light from A than B!
- $L_3$, $L_2$, $L_1$

**Chromatic Abberation**
- $F_B$, $F_G$, $F_R$
- Lens has different refractive indices for different wavelengths.

**Radial and Tangential Distortion**
- Ideal and actual points on the image plane.
Vignetting

Chromatic aberration

Radial Distortion
Radiometry and Image Formation

• To interpret image intensities, we need to understand Radiometric Concepts and Reflectance Properties.

• TOPICS TO BE COVERED:

  1) Image Intensities: Overview

  2) Radiometric Concepts:

     Radiant Intensity
     Irradiance
     Radiance
     BRDF

  3) Image Formation using a Lens

  4) Radiometric Camera Calibration
Image intensities = $f(\text{normal, surface reflectance, illumination})$

Note: Image intensity understanding is an under-constrained problem!
Radiometric concepts – boring…but, important!

(1) Solid Angle: $d\omega = \frac{dA'}{R^2} = \frac{dA \cos \theta_i}{R^2}$ (steradian)

What is the solid angle subtended by a hemisphere?

(2) Radiant Intensity of Source: $J = \frac{d\Phi}{d\omega}$ (watts/steradian)

Light Flux (power) emitted per unit solid angle

(3) Surface Irradiance: $E = \frac{d\Phi}{dA}$ (watts/m)

Light Flux (power) incident per unit surface area.

Does not depend on where the light is coming from!

(4) Surface Radiance (tricky): $L = \frac{d^2\Phi}{(dA \cos \theta_r) \ d\omega}$ (watts/m$^2$ steradian)

- Flux emitted per unit foreshortened area per unit solid angle.
- $L$ depends on direction $\theta_r$.
- Surface can radiate into whole hemisphere.
- $L$ depends on reflectance properties of surface.
The Fundamental Assumption in Vision

Lighting

Surface

No Change in Radiance

Camera
Radiance properties

- Radiance is constant as it propagates along ray
  - Derived from conservation of flux
  - Fundamental in Light Transport.

\[ d\Phi_1 = L_1 d\omega_1 dA_1 = L_2 d\omega_2 dA_2 = d\Phi_2 \]

\[ d\omega_1 = \frac{dA_2}{r^2} \quad \quad d\omega_2 = \frac{dA_1}{r^2} \]

\[ d\omega_1 dA_1 = \frac{dA_1 dA_2}{r^2} = d\omega_2 dA_2 \]

\[ \therefore L_1 = L_2 \]
Relationship between Scene and Image Brightness

- Before light hits the image plane:

  ![Diagram showing the process before light hits the image plane]

  Linear Mapping!

- After light hits the image plane:

  ![Diagram showing the process after light hits the image plane]

  Non-linear Mapping!

Can we go from measured pixel value, $I$, to scene radiance, $L$?
The camera response function relates image irradiance at the image plane to the measured pixel intensity values.

\[ g : E \rightarrow I \]
Radiometric Calibration

• Important preprocessing step for many vision and graphics algorithms such as photometric stereo, invariants, de-weathering, inverse rendering, image based rendering, etc.

\[ g^{-1} : I \rightarrow E \]

• Use a color chart with precisely known reflectances.

• Use more camera exposures to fill up the curve.

• Method assumes constant lighting on all patches and works best when source is far away (example sunlight).

• Unique inverse exists because \( g \) is monotonic and smooth for all cameras.
The Problem of Dynamic Range

- **Dynamic Range:** Range of brightness values measurable with a camera

- **Today’s Cameras:** Limited Dynamic Range

  - We need 5-10 million values to store all brightnesses around us.
  - But, typical 8-bit cameras provide only 256 values!!
High Dynamic Range Imaging

• Capture a lot of images with different exposure settings.

• Apply radiometric calibration to each camera.

• Combine the calibrated images (for example, using averaging weighted by exposures).

Images taken with a fish-eye lens of the sky show the wide range of brightnesses.
Capturing, Representing, and Manipulating High Dynamic Range Imagery (HDRI)
Dynamic Range in the Real World

Office interior
Indirect light from window
1/60th sec shutter
f/5.6 aperture
0 ND filters
0dB gain

Sony VX2000 video camera
Dynamic Range in the Real World

Outside in the shade
1/1000\textsuperscript{th} sec shutter
f/5.6 aperture
0 ND filters
0dB gain

16 times the light as inside
Dynamic Range in the Real World

Outside in the sun
1/1000th sec shutter
f/11 aperture
0 ND filters
0dB gain

64 times the light as inside
Dynamic Range in the Real World

Straight at the sun
1/10,000\(^{th}\) sec shutter
f/11 aperture
13 stops ND filters
0dB gain

5,000,000 times the light as inside
Dynamic Range in the Real World

Very dim room
1/4th sec shutter
f/1.6 aperture
0 stops ND filters
18dB gain

1/1500th the light than inside
Dynamic Range in the Real World

The real world is high dynamic range.
Ways to vary exposure

- Shutter Speed
- F/stop (aperture, iris)
- Neutral Density (ND) Filters
- Gain / ISO / Film Speed
RADIANCE Format

Greg Ward’s “Real Pixels” format

Red | Green | Blue | Exponent
--- | --- | --- | ---
(145, 215, 87, 149) = (145, 215, 87) * 2^(149-128) = (1190000, 1760000, 713000)
(145, 215, 87, 103) = (145, 215, 87) * 2^(103-128) = (0.00000432, 0.00000641, 0.00000259)

8-bit Images
(TIF, BMP, TGA, JPG, etc.)

- Useful for representing images to be output on a computer monitor or printer
- Less useful for representing images for film
- Inadequate for representing HDR images
- Usually nonlinearly encoded with a gamma curve, i.e.

- Amount of light = (pixel value)^2.2
High-Dynamic Range Photography
HDR Tone-mapping

Linear tone-mapping

Non-linear tone-mapping
HDR Shop
High Dynamic Range Image Processing and Manipulation

www.debevec.org/HDRShop