Camera Models and 3D Reconstruction I

Optics and Cameras

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Overview

• Some history
• Image formation model
  – Pinhole Camera
  – Using a lens
• Optics
  – Focal length, Focus distance and depth of field
  – Aberation and distortion
• Artistic considerations
• Imaging pipeline
  – Camera = Light-measuring device ?
SOME HISTORY
Camera obscura
Camera obscura

• Earliest written observation
  – Chinese writing dated to 4th century BC

• Experiments, optical tool and entertainment
  – In 6th century: early experiments of the Greek mathematician (Anthemius of Tralles)
    – 11th century: Ibn al-Haytham provided the first competent geometrical and quantitative descriptions of the phenomenon
    – 13th century, Arnaldus de Villa Nova is credited with using a camera obscura to project live performances for entertainment
Camera obscura

Camera Obscura in Mülheim
Largest walk-in camera obscura in the world
Birth of photography

Oldest surviving photograph of a real scene created by Nicéphore Niépce

- First experiments with silver salts
- … then light-sensitive organic substances
- Up to several days of exposure

“View from the Window at Le Gras “ (1826 or 1827)
First cameras

Creation of the Daguerreotype camera

• Copper plate coated with silver and exposed to iodine vapor
• Plate is exposed to light to create an image (up to 15 minutes)

Daguerreotype camera from 1839
[Liudmila & Nelson]
First cameras

Boulevard du Temple (1838)
First handheld film camera

Original Kodak camera (1888)
• 100-exposure roll of film
• Mail the camera back for the prints

(Smithsonian)
First handheld digital camera

Steven Sasson invented the world’s first digital handheld camera in Kodak in 1975.

- Weight 3.6kg
- Resolution 0.01MP
- From sensor to temporary memory in about 50ms
- 23s to record one image to a digital cassette tape

Credit: George Eastman House
First handheld digital camera

Credit: George Eastman House
(D)SLR cameras

1) Camera lens
2) Reflex mirror
3) Shutter
4) Sensor
5) Focusing screen
6) Condenser lens
7) Penta mirror
8) Viewfinder eyepiece
IMAGE FORMATION MODEL
Lens vs pinhole photography

Small pinhole

Larger pinhole

(London)
Lens vs pinhole photography

Small pinhole

Using a Lens

(London)
Pinhole Camera

- No distortion: straight lines remain straight
- Infinite depth of field: everything is in focus
- Problems
  - too small -> not enough light
  - too large -> blurry image
Using a lens

- Gather more light but only 1 plane in focus
OPTICS
Light

• Light is an electromagnetic radiation that can be sensed by the human eye (~400 to ~800 THz)

• Three interpretations of light
  – Light as a particle (photons)
  – Light as rays (“tracing a single photon”)
    • Useful for visibility calculations in CG (e.g., ray casting) and optics
  – Light as waves
    • Useful property $f = \frac{c}{\lambda}$
Optics – Basics

• Light can be modelled as traveling waves
• Light rays are drawn perpendicular to these waves

(La Valle)
Optics – Basics

• Diffraction causes these rays to bend
• This is case here when the wavelength is comparable to the slit size
• Geometrical optics assume
  – Wavelength is negligible compare to slit size
  – No diffraction
  – In free space rays are straight
Snell’s law of refraction

- As waves change speed at an interface, they also change direction

(W. J. Smith)
Snell’s law of refraction

- Refractive index

\[ n_i = \frac{c}{\text{speed}_i} \]
Derivation of Snell’s law of refraction
Snell’s law of refraction

- Refractive index
  \[ n_i = \frac{c}{\text{speed}_i} \]

- Snell’s law of refraction
  \[ \frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1} \]
Optics – Prism

Transiting

• from air to glass, light bends towards the normal
• from glass to air, light bends away from the normal

(La Valle)
Optics – Glass lenses

• Same principle is applied in a continuous fashion across an entire lens – lenses are “stacks of prisms”
• Light striking the surface perpendicularly does not bend
Action of simple lenses on wave fronts

(W. J. Smith)
Paraxial focusing and focusing

\[ \frac{n}{z} + \frac{n}{r} \approx \frac{n'}{r} - \frac{n'}{z'} \]
Focal length

\[ z' \approx \frac{r \ n'}{(n' - n)} \]
Lens maker’s formula

- We consider 2 spherical interfaces air-glass-air
- Case of a thin lens $d \to 0$
Lens maker’s formula

\[ \frac{1}{s_0} + \frac{1}{s_i} = (n - 1)(\frac{1}{R_1} - \frac{1}{R_2}) \]
Gaussian lens formula

\[ \frac{1}{S_o} + \frac{1}{S_i} = \frac{1}{f} \]
Gauss Ray construction

(La Valle)
Focus distance

- Move sensor relatively to the lens to focus on different distances

- At $s_o = s_i = 2f$, we have 1:1 imaging

- Not possible to focus on objects closer than focal length
Optics - Recap

Analyzed lens properties but we made several approximations
- Geometric optics
- Thins lens
- Paraxial approximation

Gaussian lens formula: Focal length, object distance and image distance
Convex and concave lenses

Positive focal length

Negative focal length

(Hecht)
Action of simple lenses on wave fronts

(W. J. Smith)
Gauss Ray construction

(Hecht)
Power of a lens

The power of a lens is defined as

\[ P = \frac{1}{f} \quad \text{units are diopters} \]

Combining lenses

\[
\frac{1}{f_{tot}} = \frac{1}{f_1} + \frac{1}{f_2}
\]

\[ P_{tot} = P_1 + P_2 \]
Thick lenses

(W. J. Smith)
Nodal points

In a thick lens, the intersections of the chief ray with the optical axis are called the *nodal points*

- For a lens in air, these coincide with the *principal points*
- The first nodal point is the *center of perspective*
Lenses perform a 3D perspective transform

- Lenses transform a 3D object into a 3D image
- The sensor extracts a 2D slice from that image
Aperture is referred to the lens diaphragm opening inside a photographic lens. It regulates the amount of light that passes through onto the sensor.
Aperture number

Aperture number allows to describe the amount of light that passes through the sensor irrespective of the focal length

\[ N = \frac{f}{A} \]

For example:
- f/2.0 on a 50mm lens means the aperture is 25mm
- it would be 50mm on a 100mm lens
Circle of confusion
Circle of confusion

\[ \frac{C}{M_T} \approx \frac{CU}{f} \]

(Levoy)
**Depth of field** is the distance between the nearest and the farthest objects that are in acceptably sharp focus.

\[ DOF \approx \frac{2u^2Nc}{f^2} \]

With

- \( c \) the given circle of confusion
- \( f \) the focal length,
- \( N \) the F-number (aperture)
- \( u \) the distance to subject
DOF and distance

\[ \text{DOF} \approx \frac{2u^2 Nc}{f^2} \]

50mm - f/3.5 - 16”

50mm - f/3.5 - 90”

(Brian Auer.)
DOF and aperture

\[ DOF \approx \frac{2u^2 Nc}{f^2} \]

(Zulkamalober)
DOF and focal length

\[
DOF \approx \frac{2u^2 Nc}{f^2}
\]

(London)
Exposure can be controlled by changing

- **Irradiance**
  - Amount of light falling on the sensor
  - Aperture directly controls irradiance

- **Time**
  - Controlled by the shutter
ABERRATION & DISTORTION
Spherical lenses

Lenses are made most often made with surfaces that are spherical which are easier to manufacture

(Wikipedia)
Spherical lenses

Lenses are made most often made with surfaces that are spherical which are easier to manufacture … but introduces aberration

(Wikipedia)
Chromatic aberration

Index of refraction varies with wavelength

- Longitudinal (axial) – Different colours focus at different depths
- Lateral (transverse) – Blue image is closer to lens, it will appear smaller
Chromatic aberration

Example of lateral lateral chromatic aberration

(Wikipedia)
Vignetting

Vignetting is the reduction brightness or saturation toward the periphery

There are several type of vignetting
- Mechanical
- Optical
- Natural
- Pixel
Field curvature

(a) (Hecht)
Radial distortion

This is due to a change in magnification with image position

Barrel distortion

Pincushion distortion
Veiling glare is a stray light that fogs images and reduces contrast.

It is caused by reflections between surfaces of lens components.

(Imatest)
ARTISTIC CONSIDERATIONS
Soft focus lens – spherical aberration
Soft focus lens – spherical aberration

CREDIT: DREAM SEQUENCE, Jolie Luo
Depth of field – Dolly zoom

(Jaws, 1975)
Bokeh is defined as the way the lens renders out-of-focus points of light.
Motion blur (Pexel)
Lens flare (veiling glare)
IMAGING PIPELINE
Camera = Light-measuring device?

Simple models assume an image is a “quantitative measurement” of scene radiance.

This assumption is made in many applications:

- Shape from shading
- HDR imaging
- Deblurring
- …
Typical color imaging pipeline (ISP)

Sensor with color filter array (CFA) (CCD/CMOS) → ISO gain and raw-image processing → RGB Demosaicing

Mapping to sRGB output → Color Manipulation (Photo-finishing) → White-Balance & Color Space Transform (CIE XYZ) → Noise Reduction

JPEG Compression → Save to file

[M. Brown, 2019]
Stage 1 – The raw image

- This is the unprocessed image produced by the sensor
- It is still in its mosaicked Bayer pattern format
Stage 1 – The raw image
Stage 1 – The raw image

- Camera RGB sensitivity is sensor specific

[From camera sensitivity database by Dr. Jinwei Gu]

- Raw-RGB represents the physical world's spectral power distributions "projected" onto the sensor's spectral filters.
Typical color imaging pipeline (ISP)

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9. JPEG Compression

[M. Brown, 2019]
Stage 2 – ISO gain and raw image processing

- The sensor signal is amplified and digitized
- In the camera the ISO setting specifies the gain to signal
- ISO gain is sensor (i.e. camera) specific

![Image: Harry Guinness]
Stage 2 – ISO gain and raw image processing

Other raw image processing tasks

- Black light subtraction

- Defective pixel mask

Image: Harry Guinness
Stage 2 – ISO gain and raw image processing

Lens field correction
- Provide a spatially varying correction
- Compensate lens distortion
- Correct uneven light fall

[Image: Measured values on the left, Desired values on the right, and a graph from Karaimer and Brown, 2016]
Stage 1 – The raw image
Stage 2 – ISO gain and raw image processing
Stage 2 – ISO gain and raw image processing
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[M. Brown, 2019]
Stage 3 – RGB demosaicing

A Bayer filter mosaic is a color filter applied on the sensor of cameras.

The objective of demosaicing is to produce a full RGB image from the incomplete color samples.
Stage 3 – RGB demosaicing

\[ \begin{align*}
\text{G5} &= \text{G2} + \text{G4} + \text{G6} + \text{G8} \\
\text{B5} &= \text{B1} + \text{B3} + \text{B7} + \text{B9}
\end{align*} \]

[M. Brown, 2019]
Stage 3 – RGB demosaicing
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[M. Brown, 2019]
Stage 4 – Noise reduction

- All sensors have noise
- Different strategies are possible
- The smaller the sensor the more aggressive the noise reduction

Image: Harry Guinness
Typical color imaging pipeline (ISP)

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[M. Brown, 2019]
Stage 5 - White balance and color transform

The objective is to convert the sensor raw-RGB values to a device independent color space (see previous lecture)

• Apply a white-balance correction to the raw-RGB values

• Map the white-balanced raw-RGB values to CIE XYZ
Stage 5 - White balance

[Illustration: Diagram showing the relationship between illuminants and their effects on a tomato.]

[M. Brown, 2019]
Stage 5 - White balance

[Sharon Albert]
The ability of the human visual system to adapt to scene illumination is called **color constancy** or **chromatic adaptation**

- Image sensors do not have this ability

- It must be performed as a processing step, i.e. “white balance”
Stage 5 - White balance

Several solutions

- User can manually set the white balance

- Camera specific white-balance matrices for common illuminations

- Auto white balance: often refer to AWB as "illumination estimation"
Stage 5 - Color transform

- Use a device independent color space such as CIE XYZ
  - XYZ values are not specific to any device
Stage 5 - Color transform

• Use a device independent color space such as CIE XYZ
  – XYZ values are not specific to any device

• Electronic devices (e.g. cameras)
  – compute mappings of their device specific values to the corresponding CIE XYZ values
  – a canonical space to match between devices (in theory !)
Stage 5 - White balance and color transform (before)
Stage 5 - White balance and color transform (after)
Typical color imaging pipeline (ISP)

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[M. Brown, 2019]
Stage 6 – Color manipulation

- Cameras apply this “manipulation" to make the images look good

- It is also possible to select various photo-finishing styles

- Smartphones often compute this per-image and may even take into account geographical region
Stage 6 – Color manipulation (tone mapping)

Darkening the image
Brightening the image
Enhancing contrast (called an S-curve)

[M. Brown, 2019]
Stage 6 – Color manipulation
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[M. Brown, 2019]
Stage 7 – sRGB mapping

- sRGB is a color space defined to be used by printers and monitors

- It assumes
  - A certain viewing condition
  - Gamma correction
Stage 7 – sRGB mapping
Typical color imaging pipeline (ISP)

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[M. Brown, 2019]
In Summary

• Basic notion on optics to understand cameras
  – Focal length
  – Depth of field
  – Aberration and distortions

• Is the camera a light-measuring device?
  – The objective of cameras is to create good looking images
  – Many non linear effects and unknown elements
Next time

• Despite all the issues we have seen, is it still possible to use the camera to understand a scene

• Our focus will on geometry
  – Recover camera pose (calibration)
  – Estimate the geometry of the scene (3d reconstruction)
Thanks