CS4501: Introduction to Computer Vision
Cameras and Image Formation

Various slides from previous courses by:
D.A. Forsyth (Berkeley / UIUC), I. Kokkinos (Ecole Centrale / UCL), S. Lazebnik (UNC / UIUC), S. Seitz (MSR / Facebook), J. Hays (Brown / Georgia Tech), A. Berg (Stony Brook / UNC), D. Samaras (Stony Brook), J. M. Frahm (UNC), V. Ordonez (UVA).
Make computers understand images and video

What kind of scene?
Where are the cars?
How far is the building?

...
Today’s Class

What is a camera?
Who invented cameras?
Image Formation
Brief Introduction to Projective Geometry (Computer Graphics)
About the Course

CS4501-008: Introduction to Computer Vision

• Instructor: Vicente Ordonez
• Email: vicente@virginia.edu
• Website: http://vicenteordonez.com/vision/
• Class Location: Thornton Hall E316
• Class Times: Monday-Wednesday 2pm - 3:15pm
• Piazza: http://piazza.com/virginia/spring2018/cs4501008/home
Pre-requisites

- Python programming skills
- Calculus / Linear Algebra / Probability
Grading

• Programming Projects: 80% (5 projects)
  (15% + 15% + 15% + 15% + 20%)

• Quiz: 20% (2 quizzes)
  (10% + 10%)
Textbook


Cameras
What do you need to make a camera from scratch?
Accidental Cameras

Accidental Pinhole and Pinspeck Cameras
Revealing the scene outside the picture.
Antonio Torralba, William T. Freeman
Accidental Cameras

a) Input (occluder present)  
b) Reference (occluder absent)

c) Difference image (b-a)  
d) Crop upside down  
e) True view
Let’s design a camera

– Idea 1: put a piece of film in front of an object
– Do we get a reasonable image?
Pinhole camera

Idea 2: add a barrier to block off most of the rays
  • This reduces blurring
  • The opening known as the aperture

Slide source: Seitz
Camera obscura
Known by the Greeks and the Chinese 470BC-322BC

Recorded in writings by Chinese Philosopher Mozi (墨子) 470-390BCE

Recorded in writings by Aristotle or one of his disciples 384-322BCE
Camera obscura: the pre-camera

Freestanding camera obscura at UNC Chapel Hill

Photo by Seth Ilys
Camera obscura
Camera Obscura used for Tracing

Lens Based Camera Obscura, 1568
First Photograph

Oldest surviving photograph
  • Took 8 hours on pewter plate

Photograph of the first photograph

Joseph Niepce, 1826

stored at UT Austin

Bitumen of Judea: Naturally occurring asphalt that is photo-sensitive
From Joseph Niepce to Louis Daguerre

- Act 1: Joseph Niepce tells his nice idea to pal Louis Daguerre

- Act 2: Good friend Louis Daguerre improves idea and names it Daguerrrotypes

- Act 3: Louis Daguerre makes history (and money).
1846 Daguerrotype of a young Abraham Lincoln

Daguerreotype camera built by La Maison Susse Frères in 1839, with a lens by Charles Chevalier
Hercules Florence’s *Photographie*

- Brazilian painter and inventor
- Before Daguerre but after Niepce
- Included the idea of negatives
George Eastman 1885 (Rochester, NY)

• Founder of pioneering Eastman Kodak Company (Kodak)

• Popularization of film photography (nitrate film)

Should look familiar if you were born in the 80’s or earlier or if you are a true modern-day hipster!
• Photo negatives
So, who invented cameras?

Maybe the wrong question to ask?
Back to the Pinhole camera

\[ f = \text{focal length} \]
\[ c = \text{center of the camera} \]
Dimensionality Reduction Machine (3D to 2D)

3D world

Point of observation

2D image
Projective Geometry

What is lost?

• Length

Who is taller?

Which is closer?
Length and area are not preserved
Projective Geometry

What is lost?

• Length
• Angles
Projective Geometry

What is preserved?

• Straight lines are still straight
Vanishing points and lines

Parallel lines in the world intersect in the image at a “vanishing point”
Vanishing points and lines

Vertical vanishing point (at infinity)

Vanishing point

Slide from Efros, Photo from Criminisi
Limitations of the Pinhole camera

- Not easy to produce a perfect pinhole in practice

- To photograph some objects you would really need a room sized camera (”camera” means literally room in Latin)

- Depending on the type of photo-sensitive material, you would need to keep the light passing through the pinhole a long time (hours? days?).
Solution? Lenses!

Figure from Szeliski for thin lens
We will mostly use the pinhole camera model however as an approximation of actual cameras.
Digital camera

• A digital camera replaces film with a sensor array
  • Each cell in the array is light-sensitive diode that converts photons to electrons
  • Two common types
    • Charge Coupled Device (CCD)
    • CMOS
Sensor Array

**FIGURE 2.17**  (a) Continuous image projected onto a sensor array. (b) Result of image sampling and quantization.
Digital Camera Pipeline

[Diagram showing the pipeline of a digital camera, including stages such as Optics, Aperture, Shutter, Sensor (CCD/CMOS), Gain (ISO), A/D, Demosaic, (Sharpen), White Balance, Gamma/curve, Compress, and DSP. The pipeline leads to RAW and JPEG formats.]
Cameras

- **Vivitar 20.1MP**
  - $30

- **Polaroid**
  - $100

- **Canon EOS C300**
  - Movie Quality
  - $40,000

- **EOS Rebel T6i**
  - $900
Netflix Approved Cameras for Content Producers

https://backloothelp.netflix.com/hc/en-us/articles/217237077-Production-and-Post-Production-Requirements-v2-1
Cameras

Apple’s Iphone X
$1000

Google’s Pixel 2 XL
$800
Cameras

Nikon D90
$1200

Nikon D3300
$700
How to Shoot Photos in Manual?

• Shutter time
• Aperture
• ISO
• Focus / Auto-focus (Yes, you can shoot in manual and also probably should focus in manual)
Small Shutter Time / Speed

Long Shutter Time
Long Shutter Time
Very Large Shutter Time – 25 seconds

https://www.davemorrowphotography.com/shutter-speed-chart
Long Shutter Time? Think of Buying a Tripod

Aluminum Tripod $140

Carbon Fiber Tripod $200

Manfrotto Mountaineer Carbon Fiber Tripod $1300
Aperture

f/2.8  f/4  f/5.6  f/8  f/11  f/16  f/22
Large vs Small Aperture + Focus Control

Large Aperture (F4.0)
Background nicely blurred

Small Aperture (F22)
Background is distracting

http://www.pgphotoclub.com/articles/aperture.html
ISO – Should be small ideally

https://www.exposureguide.com/iso-sensitivity/
In-Class Camera Demonstration
Final Thoughts - Take with grain of salt

• Shooting in Automatic, especially in low light conditions will often go the easy route of just increasing the ISO all the way up

• Sometimes in low light conditions instead you want to increase the shutter time to compensate the low light, or increase the aperture. (or use Flash)

• No shame in using Automatic in a clear day, unless trying to achieve some effect.
Projection: world coordinates $\rightarrow$ image coordinates

If $X = 2$, $Y = 3$, $Z = 5$, and $f = 2$
What are $U$ and $V$?
Projection: world coordinates $\rightarrow$ image coordinates

Camera Center $(0, 0, 0)$

$p = \begin{bmatrix} U \\ V \end{bmatrix}$

$p = \begin{bmatrix} U \\ V \end{bmatrix}$

$U = -X \cdot \frac{f}{Z}$

$U = -2 \cdot \frac{2}{5}$

$V = -Y \cdot \frac{f}{Z}$

$V = -3 \cdot \frac{2}{5}$

Sanity check, what if $f$ and $Z$ are equal?
Projection: world coordinates $\rightarrow$ image coordinates

- Camera Center $(t_x, t_y, t_z)$
- Optical Center $(u_0, v_0)$
- Projection: $P = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$
Homogeneous coordinates

Conversion

Converting to *homogeneous* coordinates

\[
(x, y) \Rightarrow \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}
\]

homogeneous image coordinates

\[
(x, y, z) \Rightarrow \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}
\]

homogeneous scene coordinates

Converting *from* homogeneous coordinates

\[
\begin{bmatrix} x \\ y \\ w \end{bmatrix} \Rightarrow \left(\frac{x}{w}, \frac{y}{w}\right)
\]

\[
\begin{bmatrix} x \\ y \\ z \\ w \end{bmatrix} \Rightarrow \left(\frac{x}{w}, \frac{y}{w}, \frac{z}{w}\right)
\]
Homogeneous coordinates

Invariant to scaling

\[
\begin{bmatrix}
    x \\
    y \\
    w
\end{bmatrix}
\]

\[
\begin{bmatrix}
kx \\
ky \\
kw
\end{bmatrix}
\]

\[
\begin{bmatrix}
kx/kw \\
ky/kw \\
w/w
\end{bmatrix}
\]

Homogeneous Coordinates \quad Cartesian Coordinates

Point in Cartesian is ray in Homogeneous
Projection matrix (Word Coordinates to Image Coordinates)

\[ x = K[R \ t]X \]

- \( x \): Image Coordinates: \((u,v,1)\)
- \( K \): Intrinsic Matrix (3x3)
- \( R \): Rotation (3x3)
- \( t \): Translation (3x1)
- \( X \): World Coordinates: \((X,Y,Z,1)\)

Intrinsic Camera Properties: \( K \)
Extrinsic Camera Properties: \([R \ t]\)
Projection matrix

Intrinsic Assumptions
• Unit aspect ratio
• Optical center at (0,0)
• No skew

Extrinsic Assumptions
• No rotation
• Camera at (0,0,0)

\[ \mathbf{x} = \mathbf{K} \begin{bmatrix} \mathbf{I} & 0 \end{bmatrix} \mathbf{X} \]

Slide Credit: Savarese
Remove assumption: known optical center

Intrinsic Assumptions
- Unit aspect ratio
- No skew

Extrinsic Assumptions
- No rotation
- Camera at (0,0,0)

\[ \mathbf{x} = \mathbf{K}[\mathbf{I} \ 0] \mathbf{X} \rightarrow \begin{bmatrix} u \\ v \\ w \\ 1 \end{bmatrix} = \begin{bmatrix} f & 0 & u_0 & 0 \\ 0 & f & v_0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \]
Remove assumption: square pixels

Intrinsic Assumptions
• No skew

Extrinsic Assumptions
• No rotation
• Camera at (0,0,0)

\[ x = K[I \ 0] X \]

\[
\begin{bmatrix}
  u \\
  v \\
  w \\
  1
\end{bmatrix}
= \begin{bmatrix}
  \alpha & 0 & u_0 & 0 \\
  0 & \beta & v_0 & 0 \\
  0 & 0 & 1 & 0 \\
  0 & 0 & 1 & 1
\end{bmatrix}
\begin{bmatrix}
x \\
y \\
z \\
1
\end{bmatrix}
\]
Remove assumption: non-skewed pixels

Intrinsic Assumptions

Extrinsic Assumptions

• No rotation
• Camera at (0,0,0)

\[ x = K[I \ 0]X \]

Note: different books use different notation for parameters
Oriented and Translated Camera
Allow camera translation

Intrinsic Assumptions  Extrinsic Assumptions

• No rotation

\[
x = K[I \ t]X \quad \Rightarrow \quad \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} \alpha & 0 & u_0 \\ 0 & \beta & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & t_x \\ 0 & 1 & 0 & t_y \\ 0 & 0 & 1 & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}
\]
3D Rotation of Points

Rotation around the coordinate axes, \textit{counter-clockwise}:

\[
R_x (\alpha) = \begin{bmatrix}
1 & 0 & 0 \\
0 & \cos \alpha & -\sin \alpha \\
0 & \sin \alpha & \cos \alpha
\end{bmatrix}
\]

\[
R_y (\beta) = \begin{bmatrix}
\cos \beta & 0 & \sin \beta \\
0 & 1 & 0 \\
-\sin \beta & 0 & \cos \beta
\end{bmatrix}
\]

\[
R_z (\gamma) = \begin{bmatrix}
\cos \gamma & -\sin \gamma & 0 \\
\sin \gamma & \cos \gamma & 0 \\
0 & 0 & 1
\end{bmatrix}
\]
Allow camera rotation

\[ x = K[R \ t]X \]
Degrees of freedom

\[ x = K[R \ t]X \]

\[
\begin{bmatrix}
   u \\
   v \\
   1
\end{bmatrix}
= 
\begin{bmatrix}
   \alpha & s & u_0 \\
   0 & \beta & v_0 \\
   0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
   r_{11} & r_{12} & r_{13} & t_x \\
   r_{21} & r_{22} & r_{23} & t_y \\
   r_{31} & r_{32} & r_{33} & t_z
\end{bmatrix}
\begin{bmatrix}
   x \\
   y \\
   z \\
   1
\end{bmatrix}
\]
Things to Remember for Quiz

• Pinhole camera model
• Focal length in the pinhole camera model
• Shutter Time / Aperture / ISO
• Homogeneous Coordinates
• Extrinsic Camera Properties and Intrinsic Camera Properties
• Describe mathematically (and intuitively) the conversion process from World Coordinates to Image Coordinates
Next Class: Light

- What determines the color of a pixel?
BRDF (Bidirectional reflectance distribution function)

\[ \rho_{bd}(\theta_o, \phi_o, \theta_i, \phi_i) = \frac{L_o(x, \theta_o, \phi_o)}{L_i(x, \theta_i, \phi_i \cos \theta_i) d\omega} \]
Questions?