Image formation

Subhransu Maji

CMPSCI 670: Computer Vision

September 13, 2016
Topics:
- deep learning, CNNs, machine learning, AI
- Applications: self driving cars, face detection/recognition, etc
- robotics, calibration, structure from motion
- graphics, text/natural language processing, speech,

Goals:
- Learn fundamentals of CV/ML/image processing
- Do a supercool project
- Get an awesome industry job (e.g., space exploration @ NASA)

Programming: 7.5 - 8.5, Math: 6.5 - 7.5

Spire: waitlisted students? there are a few more open slots
Resources for vector algebra and probability added to the webpage
Overview of the next two lectures

- The pinhole projection model
  - qualitative properties
- Cameras with lenses
  - Depth of focus
  - Field of view
  - Lens aberrations
- Digital cameras
  - Sensors
  - Colors
  - Artifacts
- Computational photography
  - Novel sensors and cameras
Cameras

Albrecht Dürer early 1500s

Brunelleschi, early 1400s
Let's design a camera

Idea 1: Let's put a film in front of an object. Do we get a reasonable image?
Pinhole camera

Object  Barrier  Film

Add a barrier to block of most rays
Pinhole camera

- Captures pencil of rays - all rays through a single point: aperture, center of projection, focal point, camera center
- The image is formed on the image plane
Camera obscura

- Basic principle known to Mozi (470-390 BCE), Aristotle (384-322 BCE)
- Drawing aids for artists: described by Leonardo Da Vinci (1452-1519 AD)

Gemma Frisius, 1558

“Camera obscure” Latin for “darkened room”
Pinhole cameras are everywhere

Tree shadow during a solar eclipse
photo credit: Nils van der Burg
http://www.physicstogo.org/index.cfm
Accidental pinhole cameras

My hotel room, contrast enhanced. The view from my window

Accidental pinholes produce images that are unnoticed or misinterpreted as shadows

A. Torralba and W. Freeman, Accidental Pinhole and Pinspeck Cameras, CVPR 2012
Home-made pinhole camera

http://www.pauldebevec.com/Pinhole
Dimensionality reduction: 3D to 2D

3D world

Point of observation

2D image

• **What is preserved?**
  • Straight lines, incidence

• **What is not preserved?**
  • Angles, lengths
To compute the projection $P'$ of a scene point $P$, form a **visual ray** connection $P$ to the camera center $O$ and find where it intersects the image plane.

- All scene points that lie on this visual ray have the same projection on the image.
- Are there points for which this projection is not defined?
**The coordinate system**
- The optical center \(O\) is at the origin
- The image plane is parallel to the xy-plane (perpendicular to the z axis)

**Projection equations**
- Derive using similar triangles

\[
(x, y, z) \rightarrow \left(f \frac{x}{z}, f \frac{y}{z}\right)
\]
Projection of a line

- What if we add another line parallel to the first one?
Vanishing points

- Each direction in space has its own vanishing point
  - All lines going in the that direction converge at that point
- **Exception**: directions that are parallel to the image plane
Vanishing points

- Each direction in space has its own vanishing point
  - All lines going in the that direction converge at that point
- **Exception**: directions that are parallel to the image plane
- What about the vanishing point of a plane?
Vanishing line of the ground plane

- All points at the same height of the camera project to the horizon
- Points above the camera project above the horizon
- Provides a way of comparing heights of objects
Is the person above or below the viewer?
Perspective cues
Perspective cues
Perspective cues
Comparing heights

vanishing point
Measuring heights

What is the height of the camera?
Masaccio, *Trinity*, Santa Maria Novella, Florence, 1425-28

One of the first consistent uses of perspective in Western art
Perspective in art

(At least partial) Perspective projections in art well before the Renaissance

Several Pompei wallpaintings show the fragmentary use of linear perspective:

From ottobwiersma.nl

Also some Greek examples,
So apparently pre-renaissance…
What does a sphere project to?
Perspective distortion

- What does a sphere project to?
Perspective distortion

- The exterior looks bigger
- The distortion is not due to lens flaws
- Problem pointed out by Da Vinci
Orthographic projection

- Special case of perspective projection
  - Distance of the object from the image plane is infinite
  - Also called the “parallel projection”
Orthographic projection

- Special case of perspective projection
  - Distance of the object from the image plane is infinite
  - Also called the “parallel projection”
Overview of the next two lectures

- The pinhole projection model
  - Qualitative properties
- **Cameras with lenses**
  - Depth of focus
  - Field of view
  - Lens aberrations
- Digital cameras
  - Sensors
  - Colors
  - Artifacts
- Novel cameras
  - Computational photography
Pinhole camera

- Captures \textbf{pencil of rays} - all rays through a single point: aperture, center of projection, focal point, camera center
- The image is formed on the \textbf{image plane}
Shrinking the aperture

- Why not make the aperture as small as possible?
  - Less light gets through
  - Diffraction effects
Shrinking the aperture
A lens focuses light on to the film

- **Thin lens model:**
  - Rays passing through the center are not deviated (pinhole projection model still holds)
A lens focuses light on to the film

- **Thin lens model:**
  - Rays passing through the center are not deviated (pinhole projection model still holds)
  - All parallel rays converge to one point on a plane located at the *focal length* $f$
A lens focuses light on to the film

- There is a specific distance at which objects are “in focus”
  - other points project on to a “circle of confusion” in the image
What is the relation between the focal length ($f$), the distance of the object from the optical center ($D$) and the distance at which the object will be in focus ($D'$)?
Thin lens formula

- Similar triangles everywhere!

\[ \frac{y'}{y} = \frac{D'}{D} \]
**Thin lens formula**

- Similar triangles everywhere!

\[
y'/y = D'/D \\
y'/y = (D' - f)/f
\]
Thin lens formula

\[ \frac{1}{D'} + \frac{1}{D} = \frac{1}{f} \]

Any point satisfying the thin lens equation is in focus.
DOF is the distance between the nearest and farthest objects in a scene that appear acceptably sharp in an image.
Varying the aperture

Large aperture = small DOF

Small aperture = large DOF
Changing the aperture size affects the depth of field

- A smaller aperture increases the range in which the object is approximately in focus
- But small aperture reduces the amount of light — need to increase the exposure for contrast
- Pinhole camera has an infinite depth of field
Field of view
Field of view
Field of view (FOV) depends on the focal length and the size of the camera retina.

\[ \phi = \tan^{-1} \left( \frac{d}{2f} \right) \]

Larger focal length = smaller FOV
Field of view, focal length

\[ \tan(\phi) \times 2f = d \]

\[ \sim (\phi) \times 2f = d \]

Large FOV, small \( f \) — Camera close to the car

Small FOV, large \( f \) — Camera far from the car
Same effect for faces

- wide-angle (short focus)
- standard
- telephoto (long focus)
Approximating an orthographic camera

Perspective

Weak perspective

Increasing focal length

Increasing distance from camera

Source: Hartley & Zisserman
The dolly zoom

- Continuously adjusting the camera focal length while the camera moves away from (or towards) the subject

The dolly zoom

- Continuously adjusting the camera focal length while the camera moves away from (or towards) the subject
- Also called as “Vertigo shot” or the “Hitchcock shot”

Example of dolly zoom from Goodfellas

Example of dolly zoom from La Haine
Image formation ...
Adminstrivia

- **Homework 01** posted
  - Due Sept 15, 1pm (That’s this Thursday before class)
  - Submissions as pdf via Moodle only
    - Any combination of Latex, Word, print + scan, etc.
- **Mini-project 1** posted
  - Due Sept 29

- **Sign up on Piazza** for announcements
  - I’ll use this as the primary place for announcements
- **Lecture slides and materials are posted on** webpage
- **TA office hours:**
  - Wednesday 3-4PM, Location: CS 245
- **Waitlisted students?**
  - Definitely talk to me after class (OH: Today, 2:30 - 3:30pm, CS 274)
Recap of the last lecture

- The pinhole projection model
  - Qualitative properties
- Cameras with lenses
  - Depth of focus
  - Field of view
  - Lens aberrations
- Digital cameras
  - Sensors
  - Colors
  - Artifacts
- Computational photography
  - Novel sensors and cameras
Lens flaws: Chromatic aberration

- Lens have different refractive indices (Snell’s law) for different wavelengths: causes color fringing

near lens center  near lens outer
Lens flaws: Spherical aberration

- Spherical lenses don’t focus light perfectly (thin lens model)
  - Rays farther from the optical axis are focused closer

objects lack sharpness
Lens flaws: Vignetting

- Reduction of image brightness in the periphery

Not all rays reach the sensor
Lens flaws: Radial distortion

- Caused by asymmetry of lenses
- Deviations are most noticeable near the periphery

barrel distortion  pincushion distortion  mustache distortion

http://clanegesselphotography.blogspot.com/  http://parkingandyou.com
Real photographic lens

- Many uses: cameras, telescopes, microscopes, etc

**fixed focal length**

**Example of a prime lens - Carl Zeiss **[Tessar]**

**adjustable zoom**

[Nikkor] 28-200 mm zoom lens, extended to 200 mm at left and collapsed to 28 mm focal length at right.

Overview

- The pinhole projection model
  - qualitative properties

- Cameras with lenses
  - Depth of focus
  - Field of view
  - Lens aberrations

- Digital cameras
  - Sensors
  - Colors
  - Artifacts

- Novel cameras
  - Computational photography
Measuring light

- **Photographic film** — strip of transparent plastic film base coated on one side with a gelatin emulsion containing light-sensitive materials
- Creates a latent image when exposed to light for short duration
- Films are then chemically developed to form a photograph
- Early films/photographic plates could only capture intensity
Early color photography

- Sergey Prokudin-Gorskii (1863-1944)
- Photographs of the Russian empire (1909-1916)
Only problem!

Homework 1: fix this by aligning the channels
C. Color photographic film — many layers of dyes and light sensitive materials to capture light of different frequencies simultaneously
  ‣ Kodak pioneered color films for making paper prints

Simultaneous measurement solves the alignment problem
  ‣ But needs complex film design and development process
Digital images

- Color images are commonly represented using 3 channels [R, G, B]
  - The color of each pixel is given by the (r,g,b) value

```matlab
>> im = imread('jelly.jpg');
>> whois im
Name       Size          Bytes  Class Attributes
         im = 428x570x3   731880  uint8
>> imshow(im);
>> imshow(im(:,:,1));
>> imshow(im(:,:,2));
>> imshow(im(:,:,3));
```

red

green

blue
A digital camera replaces the film with a sensor array

- Each cell in the array is a light-sensitive diode that converts photons to electrons
- Two common types of sensor arrays
  - Charge Coupled Device (CCD)
  - Complementary Metal Oxide Semiconductor (CMOS)

Color sensing in the camera

Color filter array
Bayer grid

Estimate missing components from neighboring values (demosaicing)

Why more green?

Human luminance sensitivity function

Demosiacing

Slide by S.Seitz
Demoscaicing

Red

Green

Blue
Problem: guess the values of ? in each of the three channels

Why is this even possible?
Interpolation

**nearest neighbor**
- copy one of your neighbors
  - ? ← \( gl \)

**linear interpolation**
- average values of your neighbors
  - ? ← \( \frac{(gt+gl+gr+gb)}{4} \)

**adaptive gradient**
- average based on nbhd. structure
  - if \( |gt-gb| > |gl-gr| \)
    - ? ← \( \frac{(gl+gr)}{2} \)
  - else
    - ? ← \( \frac{(gt+gb)}{2} \)

Similarly for the blue and red channels

**Homework 1:** implement this
Problem with demosaicing: color moiré
Fine black and white detail in the image scene is misinterpreted as color information.
Alternatives to Bayer filter

- White or “panchromatic” cells allow lights across all wavelengths
  - Better light efficiency
- How would you go about picking the best one?

Source: https://en.wikipedia.org/wiki/Bayer_filter
Computational cameras

(a) Traditional Camera

(b) Computational Camera

(c) Programmable Imaging

(d) Programmable Flash

Goal: Design a sampling pattern + interpolation algorithm that archives the best color reconstruction

Sampling patterns
- Given a nxn filter array we have $4^{(nxn)}$ possible choices
  - More choices if we allow different color filters
- Some patterns are obviously bad for reconstruction

Interpolation algorithms
- Can’t easily enumerate this space
- Non trivial algorithms for interpolation
Rethinking Color Cameras

Ayan Chakrabarti
Harvard University
Cambridge, MA
ayanc@eecs.harvard.edu

William T. Freeman
Massachusetts Institute of Technology
Cambridge, MA
billf@mit.edu

Todd Zickler
Harvard University
Cambridge, MA
zickler@seas.harvard.edu

Abstract

Digital color cameras make sub-sampled measurements of color at alternating pixel locations, and then “demosaick” these measurements to create full color images by up-sampling. This allows traditional cameras with restricted processing hardware to produce color images from a single shot, but it requires blocking a majority of the incident light and is prone to aliasing artifacts. In this paper, we introduce a computational approach to color photography, where the sampling pattern and reconstruction process are co-designed to enhance sharpness and photographic speed. The pattern is made predominantly panchromatic, thus avoiding excessive loss of light and aliasing of high spatial-frequency intensity variations. Color is sampled at a very sparse set of locations and then propagated throughout the image with guidance from the un-aliased luminance channel. Experimental results show that this approach often leads to significant reductions in noise and aliasing arti-

Bayer Pattern

Proposed Pattern

Demosaicking

Output Image

Get Luminance at Color Sampling sites

Propagate Chromaticities to All Pixels in Image

Output Image
linearly interpolate color value using intensity-based affinities

Figure 2. Propagating chromaticity with material affinities. **Left:** Chromaticities at pixels within each $K \times K$ patch are computed as convex combinations of chromaticities measured by the Bayer blocks at its corners. The combination weights are determined by four affinity maps $\alpha_j[n]$, one from each corner Bayer block $j$, that encode luminance edge information. **Right:** Affinity map showing regions of pixels with highest affinity to each block (marked in green), super-imposed on the corresponding luminance image.
increasing noise level
Learning Sensor Multiplexing Design through Back-propagation

To appear at NIPS’16

http://ttic.uchicago.edu/~ayanc/learnCFA/

Ground Truth  Bayer  CFZ  Learned
Light Stage 6

- Sample over time, lighting, viewing direction, pose

Paul Debevec’s group at USC-ICT

http://ict.usc.edu/prototypes/light-stages/
Lytro camera

- **Light field camera**: capture intensity along each direction of the light
  - Traditional cameras integrate light coming from all directions
- **A captured light field allows you re-render an image post-hoc**
More readings and thoughts

- **History of optics**, Wikipedia
- DIY [http://www.pauldebevec.com/Pinhole](http://www.pauldebevec.com/Pinhole)
- In MATLAB, compute the projection of a sphere using the perspective model and visualize the distortions
- Light stages over time [http://gl.ict.usc.edu/LightStages](http://gl.ict.usc.edu/LightStages)
- Richard Szeliski’s book, Sections 2.2.3 - 2.3.2