Introduction, Overview, Fast Forward

EE367/CS448I: Computational Imaging
stanford.edu/class/ee367
Lecture 1

Gordon Wetzstein
Stanford University
The Horse in Motion.

Illustrated by
MUYBRIDGE.

"SALLIE GARDNER," owned by LELAND STANFORD; running at a 1.40 gait over the Palo Alto track, 19th June, 1878.

The negatives of these photographs were made at intervals of twenty-seven inches of distance, and about the twenty-fifth part of a second of time; they illustrate consecutive positions assumed in each twenty-seven inches of progress during a single stride of the mare. The vertical lines were twenty-seven inches apart; the horizontal lines represent elevations of four inches each. The exposure of each negative was less than the two-thousandth part of a second.
Muybridge’s Multi-Camera Array at Stanford
What is Computational Imaging?

optics + sensing + computation
What is Computational Imaging?

1. optically encode scene information
2. computationally recover information

- new optics
- new sensors
- new illumination
- new algorithms
E&M
Wave Optics
Geometric Optics

Modern Signal Processing, Optimization, and AI
What is Light?

- light as rays
- unit: (spectral) radiance
- properties: wavelength, polarization, direction, ...
- only brief introduction & outlook for wave optics
Instructors

Gordon Wetzstein  Qingqing Zhao (TA)  Axel Levy (TA)
Motivating Examples of Products, Research, and Development in Computational Imaging
Apple iPhone 15 Pro Max

**Ultra Wide camera**
- 12MP
- 13 mm focal length
- 120° field of view
- f/2.2 aperture

**Main camera**
- 48MP
- 24 mm focal length
- 2.44 µm quad pixel
- f/1.78 aperture

**Telephoto camera**
- 12MP
- 120 mm focal length
- 5x optical zoom
- f/2.8 aperture
Light Field Cameras

Light L16

Lytro Illum

Facebook Surround 360

High-res 81MP

Post-capture Refocus

360° surround with parallax
Apple Vision Pro (supposedly) has 14 cameras!

4x front- and side-facing for SLAM.
2x for pass through.
4x for eye & face tracking.
2x for torso tracking.
1x for gesture tracking.
1x time-of-flight sensor.
Medical Imaging: CT, MRI, …
Electron Beam Detector

Ice + Molecules

Particle detection + 2D crops

1 particle per image

Micrograph

200 nm

Levy et al., ECCV 2022; NeurIPS 2022
Sensors on a Self-driving Car
“transient” image

O'Toole et al., CVPR 2017
Single-photon Avalanche Diodes

- 8-bit timestamp of photon event
- Time-to-Digital Converter (TDC)
- SPAD sensor
- Picosecond laser
- Scene
Reconstructing Transient Images

log likelihood of image formation
model with Poisson noise

prior on 3D spatio-temporal data, e.g. 3DTV, NLM, BM3D, ...

\[
\begin{align*}
\text{minimize} & \quad - \log p(h|A\tau) + \Gamma(\tau) \\
\text{subject to} & \quad 0 \leq \tau
\end{align*}
\]

3D deconvolution, closed-form solution
Splitting-based ADMM Solver:

Poisson denoising, closed-form solution
projection, closed-form solution
proximal operator of prior, closed-form solution
sum of terms, closed-form solution

\begin{algorithm}
\textbf{Algorithm 1} ADMM-based denoising and deconvolution
\begin{align*}
1: & \quad \text{for} \ k = 1 \ \text{to} \ M \\
2: & \quad \tau \leftarrow \arg \min_{\{\tau\}} \frac{1}{2} \|K\tau - z + u\|_2^2 \\
3: & \quad z_1 \leftarrow \arg \min_{\{z_1\}} -\log p(h|z_1) + \frac{\rho}{2} \|A\tau + u_1 - z_1\|_2^2 \\
4: & \quad z_2 \leftarrow \arg \min_{\{z_2\}} \mathcal{I}_{\mathbb{R}^{+}}(z_2) + \frac{\rho}{2} \|\tau + u_2 - z_2\|_2^2 \\
5: & \quad z_3 \leftarrow \arg \min_{\{z_3\}} \Gamma(z_3) + \frac{\rho}{2} \|\tau + u_3 - z_3\|_2^2 \\
6: & \quad u \leftarrow u + K\tau - z \\
7: & \quad \text{end for}
\end{align*}
\end{algorithm}

O’Toole et al., CVPR 2017
Transient Imaging Results

O'Toole et al., CVPR 2017
Transient Imaging Results

regular image

transient image

O’Toole et al., CVPR 2017
3D Imaging for Autonomous Vehicles

LIDAR (light detection and ranging)
Velodyne VLS-128
3D Imaging for Autonomous Vehicles

LIDAR (light detection and ranging)
Velodyne VLS-128
detector
pulsed laser
scanning mirrors
occluder
wall
hidden object
04.800 ns
1st bounce: 2.7 ns
3rd bounce: 4.3 ns

40 cm (2.7 ns)
24 cm (4.3 ns – 2.7 ns)
Retroreflective Mannequin Measurements

O'Toole et al., Nature 2018
Jointly optimize optics and image processing end-to-end!
Deep Optics

Training:
end-to-end in simulation

physical layer
digital layer

Loss
Deep Optics

Interpretations:
- Optical encoder, electronic decoder system
- Hybrid optical-electronic neural network

Inference:
fabricate lens or other physical components, run network
Learning Optics & CNN

Optics Design & Optimization
Low-level Image Processing, i.e. ISP
High-level Image Processing, i.e. CNN

Differentiable pipeline \(\rightarrow\) optimize end-to-end
Optics Design & Optimization

Low-level Image Processing, i.e. ISP

High-level Image Processing, i.e. CNN

All-optical CNN Layer

Fully-connected Layer
Conventional CNN Layer

Input Image  PSF  Recorded Image

All-optical CNN Layer
Hybrid Optical-Electronic CNNs

Phase-coded Aperture

4f system
input plane (DMD)  lens  Fourier plane (phase mask)  lens  output plane (camera sensor)

Chang et al., Scientific Reports 2018
Hybrid Optical-Electronic CNNs

Results:

- 2x classification accuracy for same power
- half power for same classification accuracy
Fast Forward
The Human Visual System

- anatomy of the eye
- acuity, color, 3D vision
- contrast sensitivity
- conflicts in displays
- refractive errors
Digital Photography

- optics
- aperture
- depth of field
- field of view
- exposure
- noise
- color filter arrays
- imaging processing pipeline
Computational Photography

- High-dynamic range imaging
- Tone mapping
- Burst photography & night sight
- Coded apertures
- …
Deep Learning for Computational Imaging

- Convolutional neural networks
- DnCNN
- U-Net
- ...
Optimization & Deep Learning

- Proximal gradient methods (HQS, ADMM)
- Iterative optimization with deep priors
- Solving general inverse problems in imaging
- ...

[Diagram of iterative optimization process]
Compressive Imaging

- single pixel camera
- compressive hyperspectral imaging
- compressive light field imaging
- ...

Wakin et al. 2006
Introduction to Wave Optics and Deep Optics

- Diffraction & interference
- The diffraction limit
- End-to-end optimization of optics & image processing
- Phase retrieval
- Computer-generated holography
Guest Lectures

Dr. Orly Liba  
Google Research

Prof. David Lindell  
University of Toronto

Prof. Katie Bouman  
Caltech

Axel Levy  
Stanford PhD
Class Details
(no formal) Prerequisites (but …)

- strong *programming skills*, ideally Python
- *linear algebra* (EE 263 or equivalent)
- basic knowledge of *Fourier transforms* (EE 261 or equivalent)
- maybe a bit of (statistical) signal processing (EE 278), but not absolutely required
- basic computer graphics or computer vision could be helpful, but also not required
Related, Possibly Helpful Classes

Active Stanford Classes:

• EE 292E: Image Systems Engineering Seminar (1 unit)
• EE 267: Virtual Reality (DIY HMD)
• CS 148: Introduction to Computer Graphics and Imaging
• PSYCH 221: Applied Vision and Image Systems Engineering
• EE 364A: Convex Optimization I
• EE 368: Digital Imaging Processing

Archived Classes:

• CS 178: Digital Photography
• CS 448A: Computational Photography
Related, Possibly Helpful Classes

Also helpful

- **CS 131:** Computer Vision: Foundations and Applications
- **CS 231A:** Computer Vision: From 3D Reconstruction to Recognition
- other computer vision courses:
  - EE 231B, CS 231M, CS 328, CS 331A, CS 331B, CS 431
- graphics courses: CS 248, CS 348B, CS 448
Imaging-related Activities at Stanford

- SCI – Stanford Computational Imaging Group
  - www.computationalimaging.org

- EE292E / SCIEN - weekly colloquium, info here: scien.stanford.edu
  - lots of interesting talks & interesting people
  - free food & drinks
  - every Wed, 4:30-5:50 pm in Packard 101
  - sign up for the mailing list at scien.stanford.edu
Requirements and Grading

- **6 assignments**: 50%
- **in-class midterm**: 20%
- **major final project (teams of ≤ 3)**: 30%
  - discuss project ideas with TA & instructor!
  - project proposal due: **02/23, 23:59pm**
  - final presentation (in-person poster session): **Wed 3/13**
  - reports and source code due: **Fri 3/15, 23:59pm**
Resources (see course website!)

- website: stanford.edu/class/ee367
- contact: ee367-win2324-staff@lists.stanford.edu
- office hours (TA): Wed 3-4:30pm, Location (website) & Zoom (canvas)
  discuss: homeworks, labs, lectures
- office hours (Instructor): Mon 3-4 pm, Packard 236 & Zoom (canvas)
  discuss: projects, course material, misc.
- Forum: Ed Discussion (canvas)
Tentative Schedule

http://stanford.edu/class/ee367/
What we don’t discuss

• no medical imaging, but same concept apply – medical imaging projects are encouraged!

• outlook on wave optics / diffractive imaging but not focus on this topic
Lectures and Problem sessions

• 2 lectures per week: Mo & We 1:30 – 2:50 pm in Y2E2 111 in person (recording will be available on canvas after class)

• 1 problem session (first 6 weeks): in person, see website (recording will be available on canvas after class)

• attendance strongly recommended, but everything is recorded
Assignments

• 6 assignments: mix of theory, programming, and HW1 has a bit of hands-on building
• out every Wed (starting this week), due Fri week after at 11:59pm (midnight)
• no late days! (unless something exceptional comes up)
• you can submit until that Sat 11:59pm (midnight) with 30% penalty on the full score (24h late=70% max score on HW), after that 0%
• discussion among students encouraged, but must submit own solution and acknowledge others that you discussed this with
• submission via www.gradescope.com - create account (see entry code on website)
• Pre-recorded weekly problem session on canvas
Midterm

- **Feb 28**: 80 minute, in-class midterm in Y2E2 111 (or remote with permission)

- open book: you can use internet, lecture material, etc.

- bring laptop!

- writing small Python scripts may be helpful but not required
Course Projects & Proposal

- individual or teams of up to 3 people
- 30% of your grade – plan on ~50-60 h per person!

- **Feb 23:** short project proposal = 1-2 pages with
  - motivation
  - related work
  - project overview
  - milestones, timeline & goals
  - at least 3 scientific references
  - we may ask you to revise the proposal, will assign a mentor to your team
Course Projects

- **Mar 13**: in-person project poster + demo session
  - see poster template on website
  - More details later

- SCPD students: can submit narrated video presentation
Course Projects

• **Mar 15:** report + source code due (at midnight)

• report = conference paper format ~6 pages with
  • abstract
  • introduction
  • related work
  • theory
  • analysis
  • results
  • discussion and conclusion
  • references
  • see latex template on website
Course Projects

• must also submit source code along with report!

• proposals, reports, source will be available on course website
  • only use non-copyrighted material
  • especially SCPD students: no projects that require NDA or company secrets
  • may request that source code / report may not be public – contact staff
Possible Course Projects

• be experimental!
• can use your own (related) research
• optimization or deep learning for your favorite inverse problem in imaging
• ...

Possible Course Projects

See previous course projects (proposals, reports, code, posters) on the course website!
Next Class: The Human Visual System

- anatomy of the eye
- acuity, color, 3D vision
- contrast sensitivity
- conflicts in displays
- refractive errors