Great Ideas in Computational Photography
HDR Imaging, Tone Mapping, Coded Apertures & Imaging

EE367/CS448I: Computational Imaging
stanford.edu/class/ee367
Lecture 6

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Computational Photography on your Phone

- High-dynamic-range (HDR) imaging
- Tone mapping
- Burst photography
Motivation

exposure sequence

wikipedia

-4 stops
exposure sequence
Motivation

- HDR
- Contrast reduction (scaling)
High Dynamic Range Imaging (HDRI)

Problems:
• Sensors have a limited full well capacity, pixels saturate for higher electron count
• Non-zero noise floor and ADC quantization further reduce precision

Terminology:
• dynamic range: ratio between brightest and darkest value
• quantization (i.e., precision) within that range is equally important
  → from 8 bits (256 values) to 32 bits floating point
HDRI – Overview

1. Estimate camera response curve
2. Capture multiple low dynamic range (LDR) exposures
3. Fuse LDR images into 32 bit HDR image
4. Possibly convert to absolute radiance (global scaling)
HDRI – Estimating the Response Curve

• not required when working with linear RAW images
• easiest option: use calibration chart
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![Color chart]

![Response curve graph]

e.g. JPEG
HDRI – Linearizing LDR Exposures

- capture exposure, apply lookup table

\[ I_{\text{lin}} = f^{-1}(I) \]

\[ f^{-1}(\cdot) \]

\[ 0 \quad 64 \quad 128 \quad 196 \quad 255 \]

relative radiance

pixel value

e.g. JPEG
HDRI – Merging LDR Exposures

• start with LDR image sequence $I_i$ (only exposure time $t_i$ changes)

• individual exposure is: $I_i = f(t_i X)$, $f$ is camera response function
HDRI – Merging LDR Exposures

• undo the camera response: \(I_{\text{lin}_i} = f^{-1}(I_i)\)
  
e.g., gamma function \(f(I) = I^{1/\gamma} \quad \rightarrow \quad f^{-1}(I) = I^\gamma\)
HDRI – Merging LDR Exposures

• compute a weight (confidence) that a pixel is well-exposed
  \(\rightarrow\) (close to) saturated pixel = not confident, pixel in center of
dynamic range = confident!

\[
w_{ij} = \exp\left(-4 \frac{(I_{\text{lin},ij} - 0.5)^2}{0.5^2}\right)\]

or mean pixel value, e.g. 127.5 if I in \([0, 255]\)
HDRI – Merging LDR Exposures

- compute per-color-channel-per-LDR-pixel weights

\[ w_{ij} = \exp \left( -4 \left( \frac{I_{\text{lin}_j} - 0.5}{0.5^2} \right)^2 \right) \]
HDRI – Merging LDR Exposures

• define least-squares objective function in log-space \( \rightarrow \) perceptually linear:

\[
\begin{align*}
\text{minimize}_{x} \quad O &= \sum_i w_i \left( \log(I_{\text{lin}_i}) - \log(t_i X) \right)^2 \\
\end{align*}
\]

• equate gradient to zero:

\[
\frac{\partial O}{\partial \log(X)} = -2 \sum_i w_i \left( \log(I_{\text{lin}_i}) - \log(t_i) - \log(X) \right) = 0
\]

• gives:

\[
\hat{X} = \exp \left( \frac{\sum_i w_i \left( \log(I_{\text{lin}_i}) - \log(t_i) \right)}{\sum_i w_i} \right)
\]
HDRI – Merging LDR Exposures

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  \]
HDRI – Relative v Absolute Radiance

- LDR to HDR only gives relative radiance
- scale by reference radiance to get absolute!

Image from Debevec & Malik, 1997
HDRI – Tone Mapping

- **Problem:** how to display a 32 bit HDR image on an 8 bit LDR display?

- **Solution:** tone mapping, i.e., “scale” into luminance range of display (or 0-255), while preserving high-contrast image details
Saturation

- sun overexposed
- foreground too dark
Tone Mapping w/ Simple Gamma

- gamma correction:
  \[ I = I^{\gamma} \]
- colors are washed out
Tone Mapping w/ Simple Gamma

- gamma in intensity only!
- intensity details lost
Tone Mapping w/ Bilateral Filter

Input HDR image

Intensity

Fast Bilateral Filter

Large scale (base layer)

Reduce contrast

Preserve!

Detail

Color

Output

Large scale

Detail

Color

Durand and Dorsey, 2002
Tone Mapping w/ Bilateral Filter

[Durand et al., 2002]
Tone Mapping w/ Local Laplacian Filters

- Many many more and more complicated tone mapping algorithms out there (too many to discuss here)
- Local Laplacian Filters is one of the state-of-the-art approaches

(a) input HDR image tone-mapped with a simple gamma curve (details are compressed)
(b) our pyramid-based tone mapping, set to preserve details without increasing them
(c) our pyramid-based tone mapping, set to strongly enhance the contrast of details

[Paris et al., 2011]
Burst Denoising for Low-light Imaging

• Problem: too much (Poisson) noise in low-light conditions
• Solution: capture, align, and average multiple short exposures

Guest lecture by Dr. Orly Liba from Google
Coded (Aperture) Computational Imaging
A camera aperture has (at least) two parts that can be “coded”:

1. aperture stop – attenuating pattern
2. refractive elements (lens or compound lens system)

1. attenuating coded aperture
2. refractive or diffractive coded aperture or lens system
Coded Aperture Changes PSF

In-focus photo

Out-of-focus, circular aperture

Out-of-focus, coded aperture

Veeraraghavan et al. 2007
Coded Aperture Changes PSF

Veeraraghavan et al. 2007

in-focus photo
out-of-focus, circular aperture
out-of-focus, coded aperture
Coded (Aperture) Imaging

Applications of *Coded Aperture Imaging*:
- Extended depth of field
- Monocular depth estimation

Applications of *Coded Imaging* in General:
- Motion deblurring
- High-speed, hyperspectral, light field, single-pixel imaging …
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What makes Defocus Deblurring Hard?

- out of focus blur
What makes Defocus Deblurring Hard?

1. Depth-dependent PSF scale (depth unknown)
2. PSF is usually not invertible

focal plane
circle of confusion
Extended Depth of Field

1. Problem: depth-dependent PSF scale (depth unknown)
   • engineer PSF to be depth invariant
   • resulting shift-invariant deconvolution is much easier!

2. Problem: circular / Airy PSF is usually not invertible: ill-posed problem
   • engineer PSF to be broadband (flat Fourier magnitudes)
   • resulting inverse problem becomes well-posed
Extended Depth of Field

- Two general approaches for engineering depth-invariant PSFs:
  1. move sensor / object (known as focal sweep)
  2. change optics (e.g., wavefront coding)
Extended Depth of Field – Focal Sweep

Captured focal sweep always blurry!

Conventional photo (small DOF)

EDOF image

Conventional photo (large DOF, noisy)

[Nagahara et al., 2008]
Extended Depth of Field – Focal Sweep

- noise characteristics are main benefit of EDOF
- may change for different sensor noise characteristics

SNR should be evaluation metric!
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Monocular Depth Estimation

- Problem: 3D/depth cameras are hard

- Solution: a single image contains a lot of depth cues – learn to use them for depth estimation (like humans)

[Godard et al., 2017]
Coded Apertures for Depth Estimation

point sources at different depths

free space propagation

$\{A, \Delta\}(x)$

thin lens

$s$

sensor

cross-section

$U_{\text{in}}(x)$

$U_{\text{out}}(x)$

$U_{\text{sensor}}(x')$

PSFs at depth:

0.50 m
0.57 m
0.65 m
0.77 m
0.94 m
1.21 m
1.68 m
2.78 m
8.00 m

defocus only

[Chang and Wetzstein, 2019]
Coded Apertures for Depth Estimation

[Ikoma et al., 2021]
Coded Apertures for Depth Estimation

- PSF engineering can make depth estimation more robust by encoding low-level depth information in the PSF (rather than just pictorial cues)

[Ikoma et al., 2021]
Coded Apertures in Astronomy

- some wavelengths are difficult to focus
  → no “lenses” available
- coded apertures for x-rays and gamma rays

NASA Swift

ESA SPI / INTEGRAL
Coded Apertures in Microscopy

- for low-light, coding of refraction is better (less light loss)

e.g., rotating double helix PSF
Stanford Moerner lab
Coded (Aperture) Imaging

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Motion Blur and Deblurring

- Problem: objects that move throughout exposure time will be blurred
- Motion deblurring is hard because:
  1. Motion PSF may be unknown and different for different object
  2. Motion PSF is difficult to invert
Motion Deblurring w/ Flutter Shutter

- engineer motion PSF (coding exposure time) so it becomes invertible!
Traditional Camera:
Shutter is OPEN

[Raskar et al. 2006]
Flutter Shutter Camera:
Shutter is OPEN & CLOSED
Inspired by Harold “Doc” Edgerton
Lab Setup

[Raskar et al. 2006]
Blurring = Convolution

Traditional Camera: Box Filter

Fourier magnitudes

sinc function

spatial convolution

[Raskar et al. 2006]
Flutter Shutter: Coded Filter

Preserves High Frequencies!!!

[Raskar et al. 2006]

Spatial convolution

Fourier magnitudes

Flutter Shutter: Coded Filter
License Plate Retrieval

[Raskar et al. 2006]
License Plate Retrieval
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Coded Imaging with Neural Sensors

Martel et al., 2020
References and Further Reading

HDR
-Debevec, Malik, “Recovering High Dynamic Range Radiance Maps from Photographs”, SIGGRAPH 1997

Tone Mapping
- Durand, Dorsey, "Fast Bilateral Filtering for the Display of High Dynamic Range Images", ACM SIGGRAPH 2002

Burst Photography/Denoising
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Extended Depth of Field
-Levin, Hasinoff, Green, Durand, Freeman, “4D Frequency Analysis of Computational Cameras for Depth of Field Extension”, ACM SIGGRAPH 2009
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Depth Estimation
- C. Godard, O. Aodha, G. Bostrow, “Unsupervised Monocular Depth Estimation with Left-Right Consistency”, CVPR 2017

Motion Deblurring
-Bando, Holtzman, Raskar, “Near-Invariant Blur for Depth and 2D Motion via Time-Varying Light Field Analysis”, ACM Trans. Graph. 2013

Other