Burst Photography

EE367/CS448I: Computational Imaging and Display
stanford.edu/class/ee367
Lecture 7

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Motivation

exposure sequence

-4 stops
Motivation

exposure sequence

-wikipedia

-2 stops
Motivation
Motivation

HDR contrast reduction (scaling)
Computational Photography - Overview

- high dynamic range
- super-resolution
- burst photography
- focal stack
- aperture stack
- confocal stereo
- blurry/noisy
- flash/no flash
- multi-flash
High Dynamic Range Imaging

- dynamic range: ratio between brightest and darkest value
- quantization within that range is equally important
  ➔ from 8 bits (256 values) to 32 bits floating point
HDRI – Overview

- estimate camera response curve
- capture multiple low dynamic range (LDR) exposures
- fuse LDR images into 32 bit HDR image
- possibly convert to absolute radiance (global scaling)
- application specific use:
  - image-based rendering lighting
  - tone mapping
  - ...
HDRI – Estimating the Response Curve

- not required when working with linear RAW images
- easiest option: use calibration chart
HDRI – Estimating the Response Curve

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[Diagram showing a linear RAW curve with a calibration chart on the left]
HDRI – Estimating the Response Curve

• not required when working with linear RAW images
• easiest option: use calibration chart

e.g. JPEG
HDRI – Linearizing LDR Exposures

- capture exposure, apply lookup table

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

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

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

\[ \text{pixel value} \]

\[ \text{relative radiance} \]
HDRI – Merging LDR Exposures

- start with LDR image sequence $I_i$ (only exposure time $t_i$ changes)
- individual exposure is: $I_i = f(t_iX)$, $f$ is camera response function
HDRI – Merging LDR Exposures

• undo the camera response: \( I_{\text{lin}_i} = f^{-1}(I_i) \)

  e.g. gamma function \( f(I) = I^{1/\gamma} \rightarrow f^{-1}(I) = I^\gamma \)
HDRI – Merging LDR Exposures

• compute a weight (confidence) that a pixel is well-exposed

→ (close to) saturated pixel = not confident, pixel in center of dynamic range = confident!

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

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

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

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

\[
\text{minimize}_X \quad O = \sum_i w_i \left( \log(I_{lin_i}) - \log(t_i X) \right)^2
\]

• equate gradient to zero:

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

• gives:

\[
\hat{X} = \exp \left( \frac{\sum_i w_i \left( \log(I_{lin_i}) - \log(t_i) \right)}{\sum_i w_i} \right)
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HDRI – Relative v Absolute Radiance

- LDR to HDR only gives relative radiance (HW4!)
- scale by reference radiance to get absolute!

Image from Debevec & Malik, 1997
Image-based Lighting with Light Probes

- single light probe covers light incident from (almost) entire hemisphere!
HDRI – Tone Mapping

• how to display a high dynamic range image on an LDR display?

• tone mapping: fit into luminance range of display (or 0-255), while preserving image details

• HW4
HDRI – Tone Mapping

- sun overexposed
- foreground too dark
HDRI – Global Tone Mapping

- gamma correction: \[ I = I^\gamma \]
- colors are washed out
HDRI – Global Tone Mapping

- gamma in intensity only!
- intensity details lost
HDRI – Gradient-domain Tone Mapping

- compute gradients, scale them, integrate (Poisson eq.)
HDRI – Gradient-domain Tone Mapping

- compute gradients, scale them, integrate (Poisson eq.)

[Image: Gradients and HDR image (scaled)]
HDRI – Gradient-domain Tone Mapping

[Image: Gradient-domain Tone Mapping with gradient attenuation map and tone mapped result]

[Fattal et al., 2002]
HDRI – Tone Mapping with Bilateral Filter

Input HDR image

Intensity

Color

Fast Bilateral Filter

Detail

Large scale (base layer)

Reduce contrast

Preserve!

Detail

Large scale

Color

Output

[Durand and Dorsey, 2002]
HDRI – Tone Mapping with Bilateral Filter

- difference is not too big

Gradient-space [Fattal et al.]  Bilateral [Durand et al.]
HDRI – Tone Mapping with Bilateral Filter

- bilateral “looks” a bit better
- no ground truth → it’s up to the user

Gradient-space [Fattal et al.]  Bilateral [Durand et al.]
HW4, Q1 & Q2

• Q1: HDR image fusion (from series of different LDR exposures)

• Q2: tone-map HDR image with
  • global gamma correction on all color channels
  • global gamma correction on intensity channel
  • local tone mapping with bilateral filter
Burst Photography - Overview

- basic idea: capture and merge bursts of photos (2 or more):
  - multiple exposures: HDR but also deblurring ...
  - multiple shifted low-res images: super-resolution
  - focal stack
  - aperture stack
  - noisy + blurry: denoising + deblurring
  - flash / no flash
  - multi-flash
Pixel Super-Resolution

• increase “pixel count”, not related to diffraction limit
• idea: capture multiple low-res (LR) images and fuse them into a single super-resolved (SR) image

[Ben-Ezra et al., 2004]
Pixel Super-Resolution
Pixel Super-Resolution

- LR must be sub-pixel shifted

\[
\begin{bmatrix}
    I_1 \\
    I_2
\end{bmatrix}
= \begin{bmatrix}
    A_1 \\
    A_2
\end{bmatrix}
\begin{bmatrix}
    I_{SR}
\end{bmatrix}
\]

\[b \quad \uparrow \quad A\]

stacked, measured LR images

downsampling & phase shift
Pixel Super-Resolution

- example for 1D scanline

$I_1$

$I_{SR}$

$I_2$

$b$

$A$

$I_{SR}$
Pixel Super-Resolution

- in general: system is well-conditioned for non-integer pixel shifts and super-resolution factors of 2-3x (don’t necessarily need priors)

- HW 4, Q3: solve (large-scale) pixel super-resolution with gradient descent to

$$\text{minimize} \quad \frac{1}{2} \|A I_{SR} - b\|_2^2$$
HW4 – Q3

• gradient descent: \[ x = x - \alpha A^T (Ax - b) = x - \alpha A^T r \]

Ax() is already implemented, generate your own 4 low-res images, then implement Atx() and solve
Overview of Other Techniques
Focal Stack

- Implemented in a range of products...
Aperture Stack

- what changes? exposure and depth of field – extract HDR & depth!

[f/8]

[f/4]

[f/2]
Confocal Stereo

- idea: intensity of in-focus point remains constant for varying aperture
Confocal Stereo

- capture aperture and focal stack
- for each pixel: find focus setting where aperture stack is most invariant

(Hasinoff and Kutulakos, 2006)
Confocal Stereo

[Hasinoff and Kutulakos, 2006]

photograph

estimated depth map
Low-res High-res Image Pair – Motion Deblurring

- secondary, fast, noisy, low-res camera for motion PSF estimation

[Ben-Ezra and Nayar, 2003]
Blurry / Noisy Image Pair – Motion Deblurring

- same idea, but take two images with same camera
- super short, high ISO noisy exposure for motion PSF estimation
- longer exposure with camera shake → deblur

(a) blurred image  (b) noisy image  (c) enhanced noisy image  (d) our deblurred result
Blurry / Noisy Image Pair – Motion Deblurring

(a) blurry images and true kernels

(b) noisy image

iteratively motion PSFs

[Yuan et al., 2007]
Flash / No-flash Image Pair

with flash: not noisy
without flash: noisy, but nice colors
combined

[Pettschnigg et al., 2004]
Flash / No-flash Image Pair

no flash

extract details
(e.g. bilateral filter)

denoised w/ bilateral filter

Pettschnigg et al., 2004
Multi-flash Photography

[Raskar et al., 2004]
Multi-flash Photography

[Raskar et al., 2004]
Multi-flash Photography

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Multi-flash Photography

[Raskar et al., 2004]
Multi-flash Photography

Photo

Multi-Flash

Overlay

Multi-Flash

Canny Intensity

Edge Detection

[Raskar et al., 2004]
Multi-flash Photography

[Raskar et al., 2004]
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[Raskar et al., 2004]
Multi-flash Photography

[Raskar et al., 2004]
Multi-flash Photography

[Canny et al., 2004]
Computational Photography - Overview

- high dynamic range
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- aperture stack
- confocal stereo
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→ capture and fuse multiple images
Next: Light Field Photography

- integral imaging
- plenoptic 1.0 v 2.0
- acquisition
  - sequential
  - multiplexing
  - camera array
- refocus
- Fourier slice theorem
References and Further Reading

HDR

• Mann, Picard “On Being 'Undigital' with Digital Cameras: Extending Dynamic Range by Combining Differently Exposed Pictures”, IS&T 1995
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Super-resolution

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• Ben-Ezra, Zomet, Nayar, “Jitter Camera: High Resolution Video from a Low Resolution Detector”, CVPR 2004
• Elad, Feuer, “Restoration of single super-resolution image from several blurred, noisy and down-sampled measured images” IEEE Trans. Im. Proc. 6(12), (1997)

Other

• Ben-Ezra and Nayar, "Motion Deblurring using Hybrid Imaging", CVPR 2003
• Yuan, Sun, Quan, Shum, “Image Deblurring with Blurred/Noisy Image Pairs", ACM SIGGRAPH 2007
• Hasinoff, Kutulakos, “Confocal Stereo”, ECCV 2006
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