Coded Computational Photography

EE367/CS448I: Computational Imaging and Display
stanford.edu/class/ee367
Lecture 9

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Coded Computational Photography - Overview

- coded apertures
- extended depth of field
  - wavefront coding
  - lattice lens
  - diffusion coding
  - focal sweep
- motion deblurring
  - flutter shutter
  - motion invariance

[Raskar et al., 2006]
[Cossairt et al., 2010]
Remember Apertures?

- out of focus blur

focal plane

circle of confusion
What makes Defocus Deblurring Hard?

1. depth-dependent PSF scale (depth unknown)
2. circular / Airy PSF is not (well) invertible
Coded Computational Imaging - Motivation

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

2. circular / Airy PSF is not (well) invertible: ill-posed problem
   • engineer PSF to be broadband (flat Fourier magnitudes)
   • resulting inverse problem becomes well-posed
Computational Imaging

1. optically encode scene information
2. computationally recover information

• new optics
• new sensors
• new illumination
• new algorithms
Coded Computational Imaging (for this Class)

1. optically encode scene information using invertible (and possibly invariant) PSF
2. computationally recover information (easy because of engineered PSF)

- new optics
- easier algorithms!
Coded Computational Imaging (for this Class)

idea applies to

• coded apertures
• extended depth of field / DOF deblurring
• extended motion / motion deblurring

• new optics
• easier algorithms!
Before going to Advanced Techniques for DOF Deblurring, let’s take a look at Coded Apertures
Apertures Revisited

- two important parts:
  1. aperture stop – attenuating pattern
  2. refractive element (lens or compound lens system)

1. attenuating coded aperture: e.g., MURA pattern
2. refractive coded aperture: e.g., cubic phase plate
Coded Aperture Changes PSF

Veeraraghavan et al. 2007

Canon EF 100 mm f/1.2L Lens
Canon SLR Rebel XT camera

Mask
Aperture

in-focus photo
out-of-focus, circular aperture
out-of-focus, coded aperture
Coded Aperture Changes PSF

Veeraraghavan et al. 2007
Coded Aperture Changes PSF

- preserves high frequencies
- deconvolution well-posed!

Veeraraghavan et al. 2007

[Image of conventional and coded aperture comparisons with FFT plots]
Coded Aperture Allows for Depth Estimation

- introduce zeros in Fourier domain
- better depth discrimination
- worse invertibility

[Levin et al. 2007]
Coded Aperture Allows for Depth Estimation

- deconvolution with strong prior necessary

[Levin et al. 2007]
In Astronomy

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

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

  e.g., rotating double helix PSF
  Stanford Moerner lab

  e.g., cubic phase plate for depth-invariant imaging
Extended Depth of Field
Depth Invariant PSFs - Overview

- two general approaches:

1. **move sensor / object**  
   (known as focal sweep)

2. **change optics**  
   (e.g., wavefront coding)
Focal Sweep

linear motion:

[Exposure]

[Sensor-Lens]
Focal Sweep

two points at different distance

[Nagahara et al. 2008]
Focal Sweep

\[ t_1 \]

 instantaneous PSF

two points at different distance
Focal Sweep

Nagahara et al. 2008

time

distance

sensor-lens

∫

PSF 1

PSF 2

t_1

t_2

instantaneous PSF

two points at different distance

[Equation]

[Graph]
Focal Sweep

\[
\int_{t_1}^{t_3} \text{PSF}_1 \, dt = \int_{t_1}^{t_3} \text{PSF}_2 \, dt
\]

instantaneous PSF

two points at different distance

[Nagahara et al. 2008]
Focal Sweep

\[ \int_{t_1}^{t_2} \int_{t_3}^{t_4} \text{PSF 1} \]
\[ \int_{t_1}^{t_2} \int_{t_3}^{t_4} \text{PSF 2} \]

instantaneous PSF

two points at different distance

[Nagahara et al. 2008]
Focal Sweep

\[ \int_{t_1}^{t_2} dt = \int_{t_3}^{t_4} dt = \approx \text{PSF}_1 \]

\[ \int_{t_5} dt = \text{PSF}_2 \]

instantaneous PSF

two points at different distance

distance sensor-lens

time

Nagahara et al. 2008
Focal Sweep

\[
\int dt = \approx \text{PSF 1}
\]

\[
\int dt = \approx \text{PSF 2}
\]

instantaneous PSF

integrated PSF

two points at different distance

[Nagahara et al. 2008]
Focal Sweep

• spend equal amount of time at each depth to make depth invariant!
Focal Sweep

captured focal sweep always blurry!

[Caption: Nagahara et al. 2008]

conventional photo (small DOF)

EDOF image

conventional photo (large DOF, noisy)
Focal Sweep

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

SNR should be evaluation metric!
Wavefront Coding

• how to obtain a depth invariant PSF without mechanically moving parts
  → change the lens!
• for many, this is the dawn of computational imaging!

• tricky to understand intuitively, so let’s try to understand what it does by looking at something...

[Dowski and Cathey 1995]
Lattice Focal Lens

superimpose array of lenses with different focal lengths!
Lattice Focal Lens

conventional camera

lattice focal lens

all-in-focus image from lattice focal lens

[Levin et al. 2009]
Extended Depth of Field (EDOF)

- remember focal sweep: move sensor s.t. same time for each depth

- lattice focal lens: same idea, but no sweeping (optical overlay) – optimal in 4D

- cubic phase plate: same idea (optimal in 2D, not optimal in 4D) (can look at this in more detail if we have time)
Diffusion Coded Photography

- can also do EDOF with diffuser as coded aperture, has better inversion characteristics than lattice focal lens

[Cossairt et al. 2010]
Back to Coding Motion
Flutter Shutter

- engineer motion PSF (coding exposure time) so it becomes invertible!
photo with coded motion
Input Photo

Deblurred Result

[Raskar et al. 2006]
Traditional Camera

Shutter is OPEN

[Raskar et al. 2006]
Flutter Shutter

[Raskar et al. 2006]
Shutter is OPEN and CLOSED

[Raskar et al. 2006]
Lab Setup
Blurring = Convolution

Traditional Camera: Box Filter

sinc Function

Fourier magnitudes

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

Preserves High Frequencies!!!

[Raskar et al. 2006]

spatial convolution

Fourier magnitudes

Flutter Shutter: Coded Filter
Comparison

[Raskar et al. 2006]
Inverse Filter Unstable

Inverse Filter stable

[Raskar et al. 2006]
Short Exposure

Long Exposure

Coded Exposure

Ground Truth

Matlab Richardson-Lucy

Our result
Are all codes “good”?

- All ones
- Alternate
- Random
- Our Code

[Raskar et al. 2006]
License Plate Retrieval
License Plate Retrieval

[Raskar et al. 2006]
Motion Invariant Photography

- making motion PSFs invariant is great, BUT need to know motion direction and velocity!

- we have already seen that focal sweep makes the PSF almost depth invariant

- how about making motion PSFs motion invariant?
Controlling Motion Blur

[Levin et al. 2008]
Can we control motion blur?

[Levin et al. 2008]
Controlling Motion Blur

Static recorded image

Tracking sensor displacement

[Levin et al. 2008]
Controlling Motion Blur

Static-recorded image

Tracking-recorded image

[Levin et al. 2008]
Controlling Motion Blur

Static-recorded image

Tracking-recorded image

Motion invariant blur

[Levin et al. 2008]
Sensor position $x(t) = at^2$

- start by moving very fast to the right
- continuously slow down until stop
- continuously accelerate to the left

- Intuition:
  - for any velocity, there is one instant where we track perfectly
  - all velocities captured same amount of time
Motion Invariant Blur

Static-recorded image

Tracking-recorded image

Parabolic-recorded image

[Levin et al. 2008]
Static camera

Unknown and variable blur kernels

Our parabolic input

Blur kernel is invariant to velocity

Our output after deblurring

NON-BLIND deconvolution
Frequency Domain

Primal Domain

Objects

sensor integration

Primal Domain

Frequency Domain

$\omega_i$, $\omega_x$

[Levin et al. 2008]
Next: Noise

- Gaussian noise
- Poissonian noise
- Denoising
References and Further Reading

Extended Depth of Field (EDOF)
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- Cossairt, Nayar “Spectral Focal Sweep for Extending Depth of Field”, Proc. ICCP 2010

Coded Apertures
- ZHOU, C., AND NAYAR, S. 2009. What are Good Apertures for Defocus Deblurring? In ICCP ’09

Coding Motion

Motion and Depth Invariance
- Bando, Holtzman, Raskar, “Near-Invariant Blur for Depth and 2D Motion via Time-Varying Light Field Analysis”, ACM Trans. Graph. 2013
- Bando, “An Analysis of Focus Sweep for Improved 2D Motion Invariance”, IEEE CVPR CCD Workshop 2013