Image and Depth from a Conventional Camera with a Coded Aperture - 2007

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Modified slides from author’s website
http://groups.csail.mit.edu/graphics/CodedAperture/
**Problem:** Variable blur in sub image

**Proposed Solution:**
- defocus -> depth -> image

**Limitations**

**Possible Applications**

**Desired bokeh**

**Undesired blur**

Present cameras- computational photography
Problem Statement

50mm Canon

Table front: 2m
Table back: 3m

Front in focus
Empty coke can, the bottles at back are at different levels of defocus
Lens and defocus

Image of a defocused point light source

Lens’ aperture

Object

Lens

Camera sensor

Focal plane
Lens and defocus

Lens' aperture

Image of a defocused point light source

Object

Focal plane

Lens

Camera sensor

Point spread function
Defocus as local convolution

Input defocused image

\[ y' = f_k \star x \]

Local sub-window
Calibrated blur kernels at depth = \( k \)

Sharp sub-window

Depth \( k = 2.7 \text{m} \):

Depth \( k = 2.5 \text{m} \):

Depth \( k = 2.1 \text{m} \):
Solution Concept

evaluate local sections

derive Blur scale k

calibrate coded camera ‘k’

single input image:

assemble depth map

all-focused image
Contributions

• Coded aperture (mask inside lens)
  - make defocus patterns different from natural images
  - Select patterns with different frequency nulls for different depth.

• Exploit prior on natural images
  - Improve deconvolution
  - Improve depth discrimination
Coded Apertures
Build your own coded aperture
Aperture filter design requirements

Algorithm:
• Reliable discrimination between the blurs that result from different scaling of the filter
• Easily invertible so that the sharp image may be recovered.

Other:
• Binary symmetric masks
• Simple construction
• Avoid radial distortion
• Minimum hole size diffraction limited

Figure 4: A simple 1D example illustrating how the structure of zeros in the frequency domain shifts as a toy filter is scaled in the spatial domain.
Scale estimation effect

Estimated image = Observed image

Filter, correct scale

Filter, wrong scale

Boost near frequency null

Spatial ringing
Analytically search for a pattern maximizing discrimination between images at different defocus scales (Kullback-Leibler divergence).
Coded aperture advantage

Larger scale

Correct scale

Smaller scale
Deconvolution
Deconvolution is ill posed

\[ f \otimes x = y \]
Deconvolution is ill posed

\[ f \otimes x = y \]

Solution 1:

Solution 2:
Deconvolution with prior

\[ x = \arg \min \left\{ \left| f \otimes x - y \right|^2 + \lambda \sum_i \rho(\nabla x_i) \right\} \]

Convolution error

Derivatives prior

Equal convolution error

Low

High
Depth Map and Image Reconstruction
1. Deconvolve entire image “y” with all the “k” blur kernels - results in “k” deconvolved estimation “x”

2. SubImage:
   1. derive reconstruction error for each blur kernel - results in “k” errors
   2. Derive corresponding “k” error energies in a window for each pixel.
   3. Minimum error energy “k” corresponds to the depth of pixel.
Regularizing Depth Estimate

Estimating best depth for each sub image windows is noisy.
Passive depth estimates needs texture.
Deconvolution may not result in unique solution.

Markov random field is used to regularize the local depth map.

Concept: Energy minimization; iterative concept
depth to be piece-wise constant; present depends only on previous
depth discontinuities should align with image discontinuities.
Summary

deblurring with 10 different aperture scales

\[ x = \arg \min \left( \left| f \otimes x - y \right|^2 + \lambda \sum_i \rho(\nabla x_i) \right) \]

Convolution error + Derivatives prior

Keep minimal error scale in each local window + regularization

Blurred Input Local depth estimation Regularized depth Recovered output
Observations
Limitations & contributions

Coded aperture reduces the amount of light

PSF is calculated at discrete depths and is not an analytical function

PSF is assumed constant at a depth irrespective of the angle (lens distortions are not taken into account)

Segmentation method is not robust and needs manual intervention sometimes

The above topics are actively researched and new algorithms for PSF engineering and segmentations are reported.

The camera manufacturers use blur calculations for passive auto focus
Application: Digital refocusing from a single image

Limited Camera models
Adequate computational power
Unlimited blur / cluttered images
Limitless imagination
Now: Flexible Camera
Image enhancements applications

1. Variable Focal length:
   Wide angle to Tele photo

2. Manual Setting control:
   Aperture, Shutter speed, ISO control

3. Digital enhancement software:
   Photo shop, …etc
Emerging: Computational Photography

Light field (Lenslet) camera - 2012

Pin hole revisited – Ansel Adams - 1941

Stereo camera - 2012
Thank you
motion blur, noise, defocus blur
Circle of Confusion (blur diameter)

Aperture: f/1.4
Subject: 1 meter distance
Background: 4 meter – 256 meter
Focal length: 50mm to 400 mm
Blur diameter: 1.2 mm – 15 mm

http://lewiscollard.com/technical/background-blur/
scale discrimination

\[ D_{KL}(P_{k_1}, P_{k_2}) = \sum_{v, \omega} \left( \frac{\sigma_{k_1}(v, \omega)}{\sigma_{k_2}(v, \omega)} \right) - \log \left( \frac{\sigma_{k_1}(v, \omega)}{\sigma_{k_2}(v, \omega)} \right) \]

\[ D_{KL}(P_{k_1}(y), P_{k_2}(y)) = \int_{y} P_{k_1}(y) \left( \log P_{k_1}(y) - \log P_{k_2}(y) \right) dy \]
Deconvolution Norms

\[ x^* = \text{argmin} \frac{1}{\eta^2} |C_{f_k}x - y|^2 + \alpha |C_{g_x}x|^2 + \alpha |C_{g_y}x|^2 \] (10)

\[ A = \frac{1}{\eta^2} C_{f_k}^T C_{f_k} + \alpha C_{g_x}^T C_{g_x} + \alpha C_{g_y}^T C_{g_y} \quad b = \frac{1}{\eta^2} C_{f_k}^T y \] (11)

\[ |C_{f_k}x - y| + \sum_{ij} \rho (x(i, j) - x(i+1, j)) + \rho (x(i, j) - x(i, j+1)) \] (12)
MRF: Minimize energy

\[ E(\tilde{d}) = \sum_i E_1(\tilde{d}_i) + \nu \sum_{i,j} E_2(\tilde{d}_i, \tilde{d}_j) \]  

(16)

where the local energy term is set to

\[ E_1(\tilde{d}_i) = \begin{cases} 0 & \tilde{d}_i = d_i \\ 1 & \tilde{d}_i \neq d_i \end{cases} \]

Penalize noisy variations - smoothen depth map - depth to be piece-wise constant

\[ E_2(\tilde{d}_i, \tilde{d}_j) = \begin{cases} 0 & \tilde{d}_i = \tilde{d}_j \\ e^{-(y_i - y_j)^2/\sigma^2} & \tilde{d}_i \neq \tilde{d}_j \end{cases} \]

Penalize changes that do not coincide with the image edges