Modeling and Synthesis of Aperture Effects in Cameras

Douglas Lanman, Ramesh Raskar, and Gabriel Taubin

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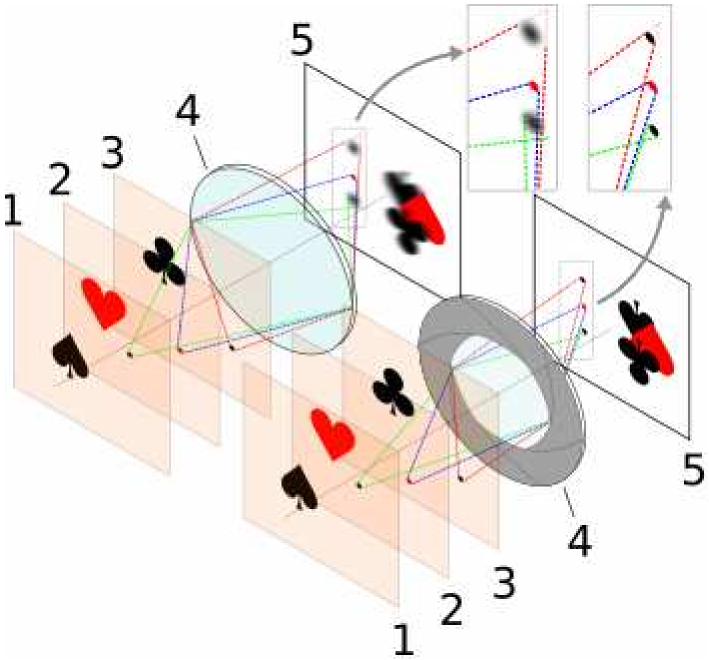
Outline

- *Introduction and Related Work*
- Modeling Vignetting
- Synthesizing Vignetting
- Experimental Results
- Conclusions and Future Work

Motivation



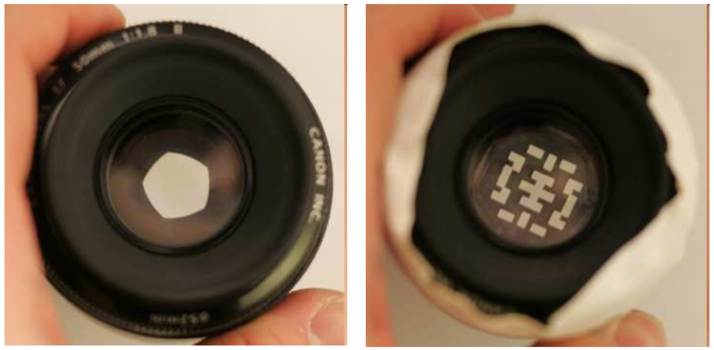
Aperture Effects in Cameras

- While capturing all-in-focus images, small apertures (pinholes) are impractical due to limited exposures required by lighting or motion
- For larger apertures, *depth of field* effects are observed, including: (1) spatially-varying blur depending on depth, and (2) vignetting
- We present simple approaches to model and control these effects

Related Work

Radiometric Camera Calibration

- Source of non-idealities [Litvinov '05]
- “Flat-field” vignetting calib. [Yu ‘04]
- Single-image calib. [Zheng '06]
- Image mosaics [D’Angelo '07]



Coded-Aperture Imaging

- Useful for deblurring [Levin '07]
- Can be applied to capture light field photographs [Veeraraghavan '07]

Variable-Aperture Photography

- Aperture bracketing [Hasinoff '06]
- Confocal stereo [Hasinoff '07]

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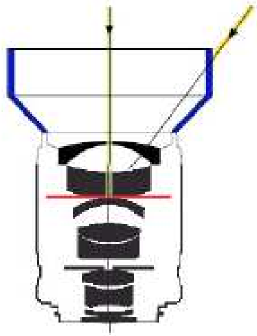
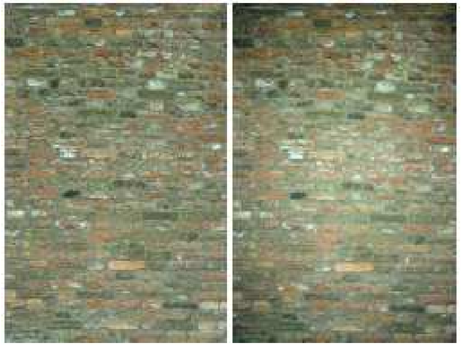
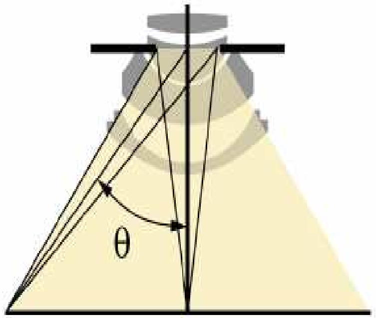
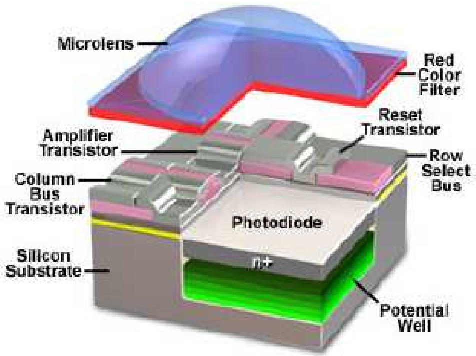
Sources of Vignetting









Mechanical Vignetting:

- Due to physical obstructions (lens hoods, filters, etc.)
- Can completely block light from reaching certain regions

Optical Vignetting:

- Occurs in multi-element optical designs, due to decrease in clear area (exit pupil) off-axis
- Reduced using small apertures

Natural and Pixel Vignetting:

- Combines physics effects: (inverse-square fall-off of light, Lambert's law, foreshortening)
- Occlusion due to pixel depth

Geometric Model: Spatially-varying PSF

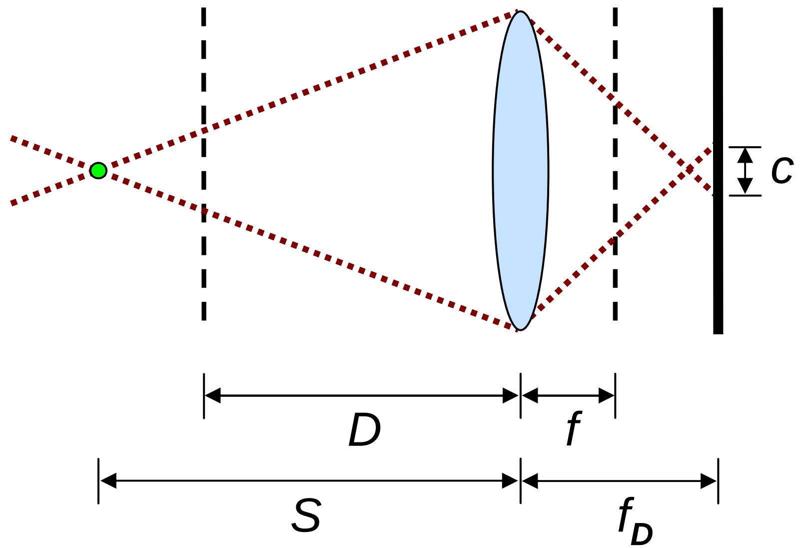
- The distance ***D*** to the in-focus "object" plane for a thin lens is given by:

$$\frac{1}{f} = \frac{1}{f_D} + \frac{1}{D}$$

- The image of an out-of-focus point at ***S*** will be a blurred region of width ***c***, where:

$$c = \frac{|S-D|}{S} \cdot \frac{f^2}{N(D-f)}$$

- This model predicts that the PSF will scale according to the object distance ***S*** and the f-number ***N*** – requiring a calibration procedure to sample both parameters.



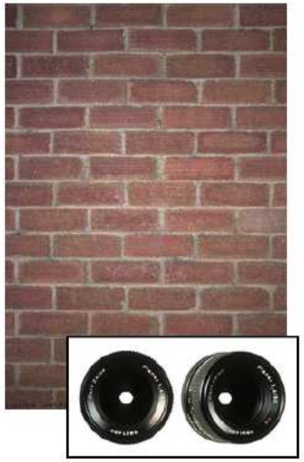
- However, as noted by Hasinoff and Kutulakos, the effective blur diameter $\tilde{c}$ is given by the following linear relation.

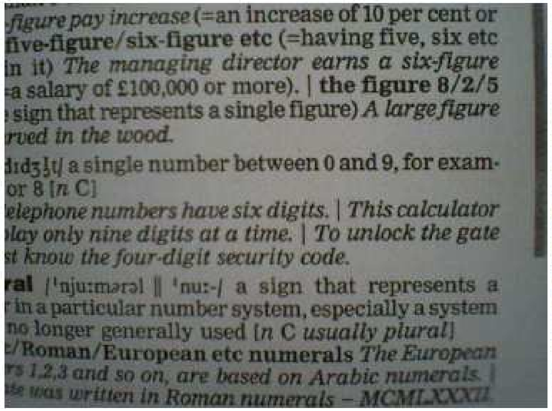
$$\tilde{c} = \frac{|S-D|}{S} A$$

- For this approximation, the spatially-varying PSF can be estimated from a single image, and is given by:

$$B_{\tilde{c}}(s,t;x,y) = \frac{1}{\tilde{c}^2} B_{\tilde{c}}\left(s,t;\frac{x}{\tilde{c}},\frac{y}{\tilde{c}}\right)$$

Photometric Model: Radial Intensity Fall-off




-figure pay increase (=an increase of 10 per cent or
five-figure/six-figure etc (=having five, six etc
in it) The managing director earns a six-figure
-a salary of £100,000 or more). | the figure 8/2/5
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ral /ˈnjuːmərəl ‖ ˈnuː-/ a sign that represents a
r in a particular number system, especially a system
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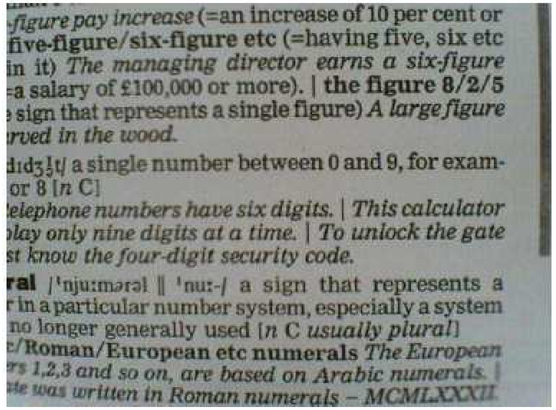
original image



vignetting-corrected

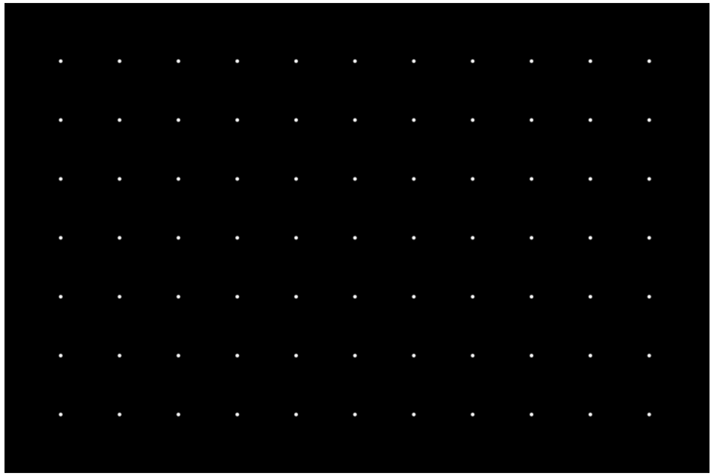
Photometric Vignetting Model

- As we have shown, various sources of vignetting result in a radial reduction in brightness that increases towards the image periphery
- Can be modeled as a low-order polynomial surface
- For known zoom, focal length, and aperture, traditional solution is to divide image intensity by a “flat-field” calibration image taken with a uniform white light area source (e.g., a light box)
- Unfortunately, this approach cannot simultaneously estimate the PSF

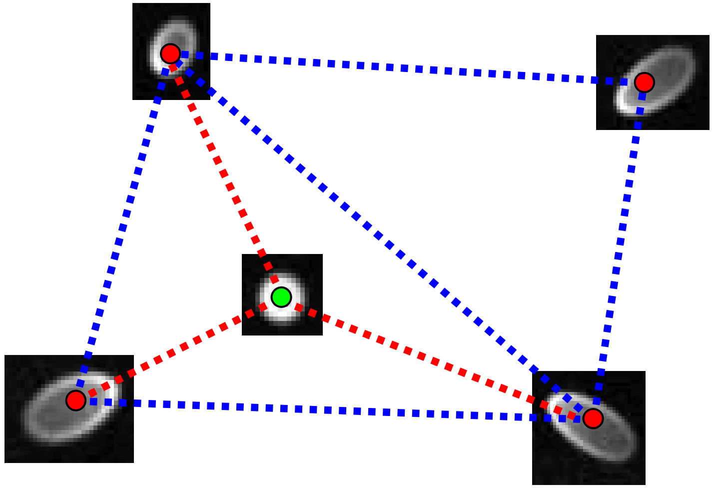
Experimental Vignetting Calibration

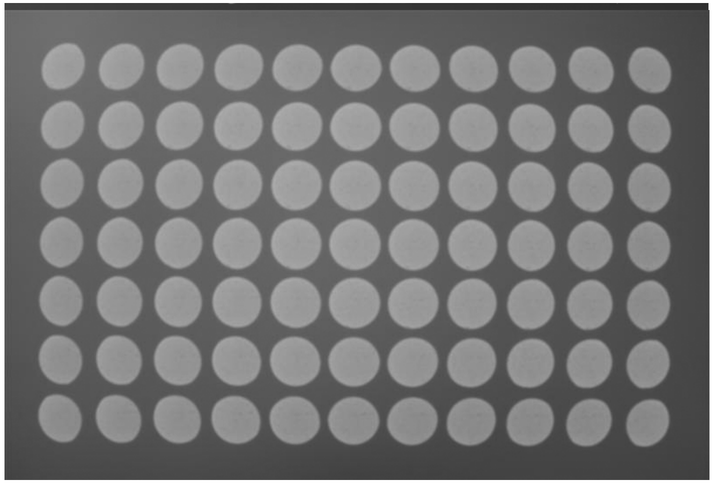
Calibration using Point Sources

- To obtain *simultaneous* estimates of the spatially-varying PSF and intensity fall-off, we use a point source array for calibration
- We observe that the image of a point light directly gives PSF (i.e., impulse response)
- Sparse PSFs → dense (i.e., per-pixel) PSFs using triangle-based interpolation



calibration pattern

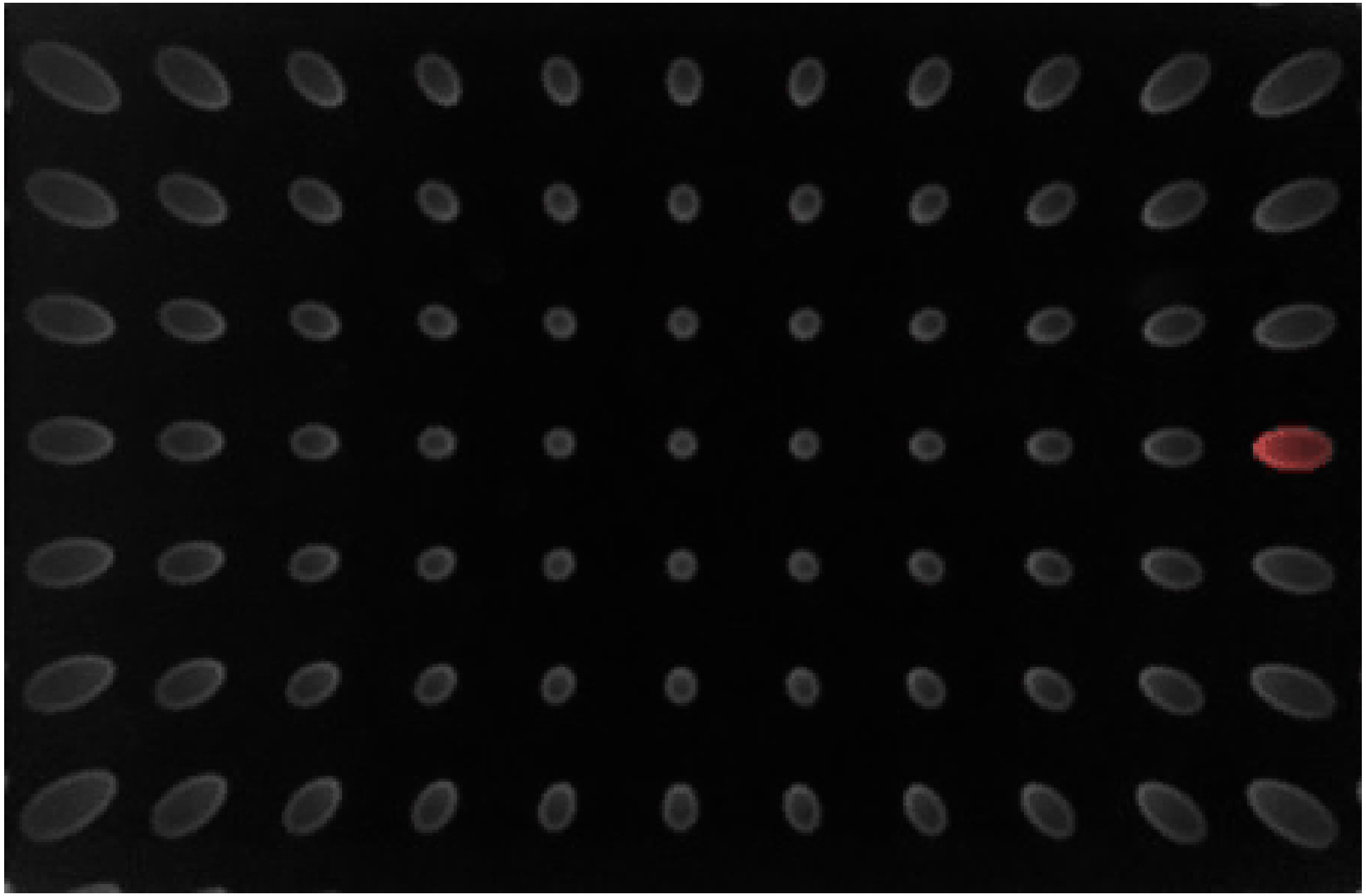




“star-shaped aperture” image

“open aperture” image

Experimental Vignetting Calibration



Note: Gray kernels are images of point lights, red is linearly-interpolated

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Vignetting Synthesis: The *Bokeh Brush*

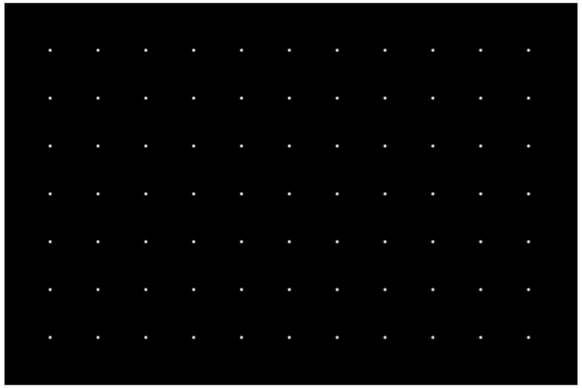
Goal:

- We desire the ability to control the spatially-varying PSF *post-capture*
- Since the spatially-varying PSF is related to the shape of out-of-focus points, this goal is equivalent to controlling *bokeh*
- We will develop a "***Bokeh Brush***"

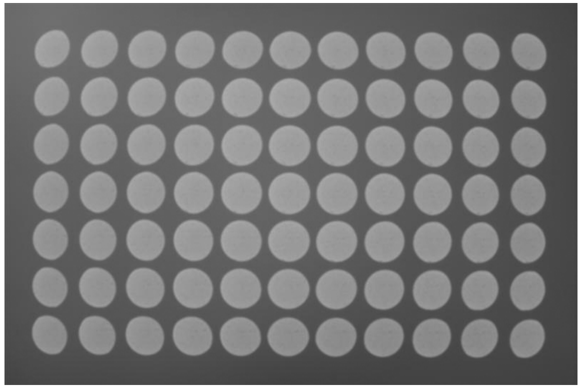
examples of bokeh

Observation:

- PSF and aperture are closely-connected…



calibration object



"open circular aperture"

"star-shaped aperture"

Vignetting Synthesis: Superposition Principle

Superposition Principle

- For unit magnification, the recorded image irradiance $I_i(x,y)$ at a pixel (x,y) is

$$I_i(x,y) = \iint_{\Omega} B(s,t;x,y) I_o(s,t)\, ds\, dt$$

  where Ω is the domain of the image, $I_o(x,y)$ is the object plane irradiance, and $B(s,t;x,y)$ is the spatially-varying PSF

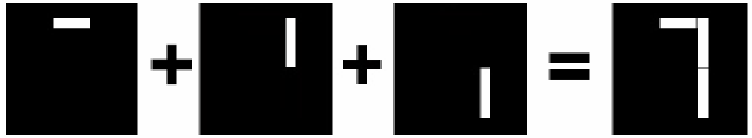
- We can express the PSF using N basis functions $\{B_i(s,t;x,y)\}$, such that

$$I_i(x,y) = \sum_{i=1}^{N} \lambda_i \iint_{\Omega} B_i(s,t;x,y) I_o(s,t)\, ds\, dt$$

- Since the PSF and aperture are directly related, we collect a sequence of basis images using the apertures $\{A_i(s,t;x,y)\}$

$$A(s,t;x,y) = \sum_{i=1}^{N} \lambda_i A_i(s,t;x,y)$$

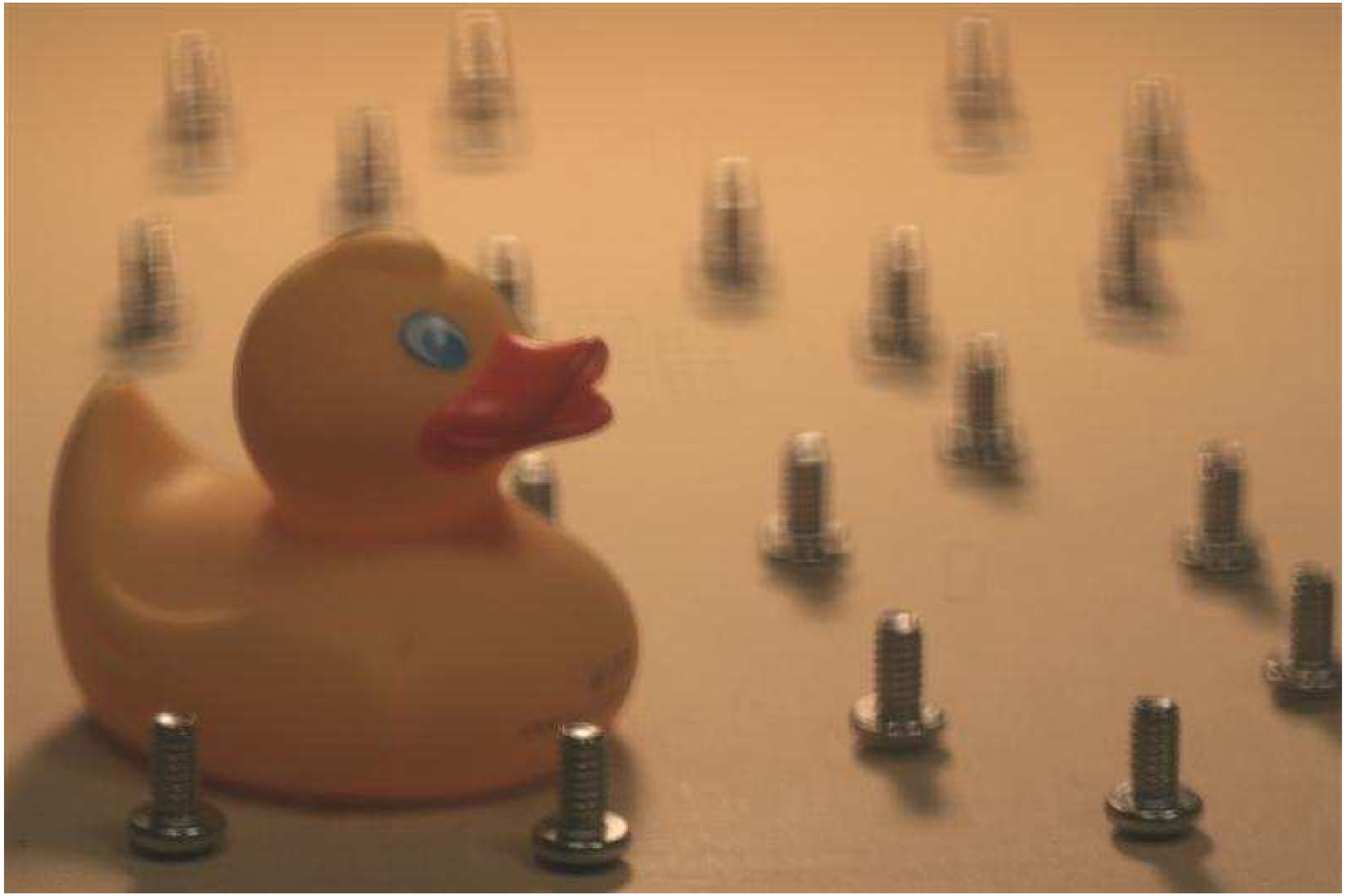
- Basis images can be linearly-combined to synthesize the image for any aperture, so long as the basis is a good approximation



Aperture Superposition: Lens Modifications

- Canon EOS Digital Rebel XT with a Canon EF 100mm 1:1.28 Macro Lens
- Modified to allow manual insertion of aperture patterns directly into the plane of the iris (i.e., by removing the original lens diaphragm)

Aperture Superposition: Laboratory Results

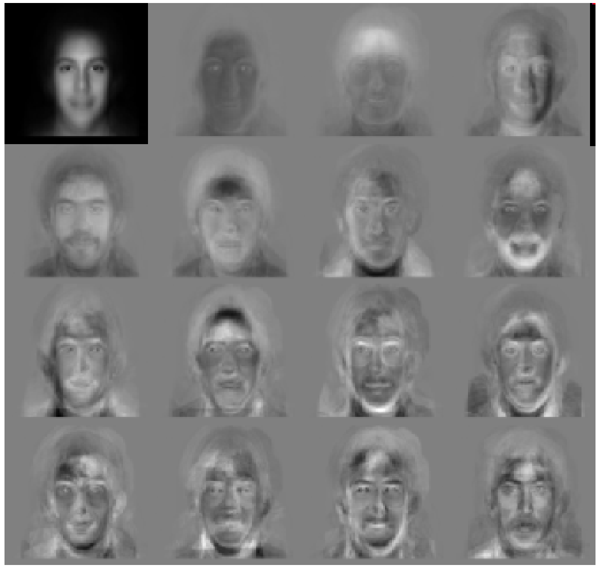


Note: Synthesized “7-segment” images using aperture superposition

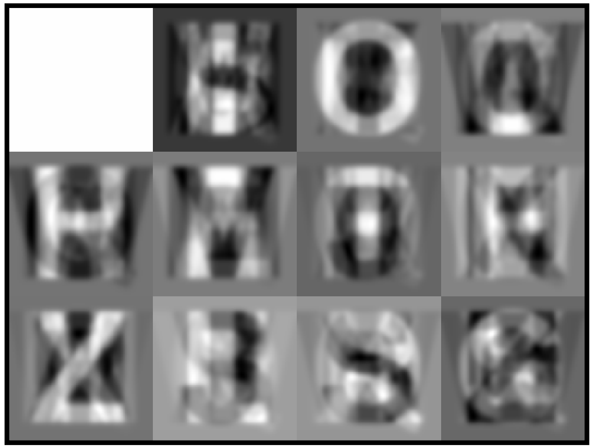
Bokeh Synthesis using PCA

Applying Principal Components Analysis:

- Although we have shown that images with different apertures can be linearly-combined, we still require an efficient basis
- One solution is to use a set of translated pinholes (equivalent to recording the incident light field)
- But, specialized bases can be used to achieve greater compression ratios…
- Here we develop a positive-valued PCA basis



training apertures



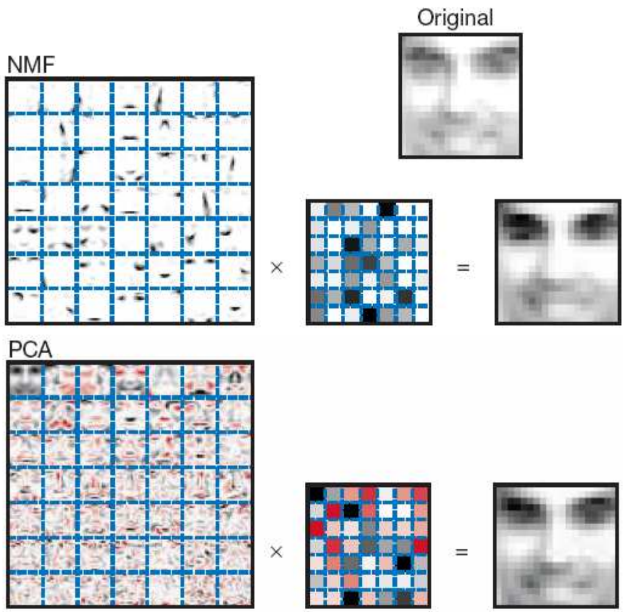
basis apertures from PCA

reconstruction results

Bokeh Synthesis using NMF

Applying Non-negative Matrix Factorization:

- Rather than normalizing PCA basis, we can find non-negative apertures directly using NMF
- NMF developed by Lee and Seung [1999] and involves iteratively-solving for *positive* basis
- NMF eliminates "open" and "bias" apertures used by PCA, reducing total number of apertures
- Unfortunately, NMF basis is not unique



training apertures **basis apertures from NMF** **reconstruction results**

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Spatially-varying Deblurring

original image

uniformly-defocused image

deblurred (mean PSF)

deblurred (spatially-varying PSF)

- Example of simulated spatially-varying blur (i.e., invariant to scene depth)
- Deblurred with estimate of spatially-varying PSF from proposed method

Vignetting Synthesis: Simulated Results

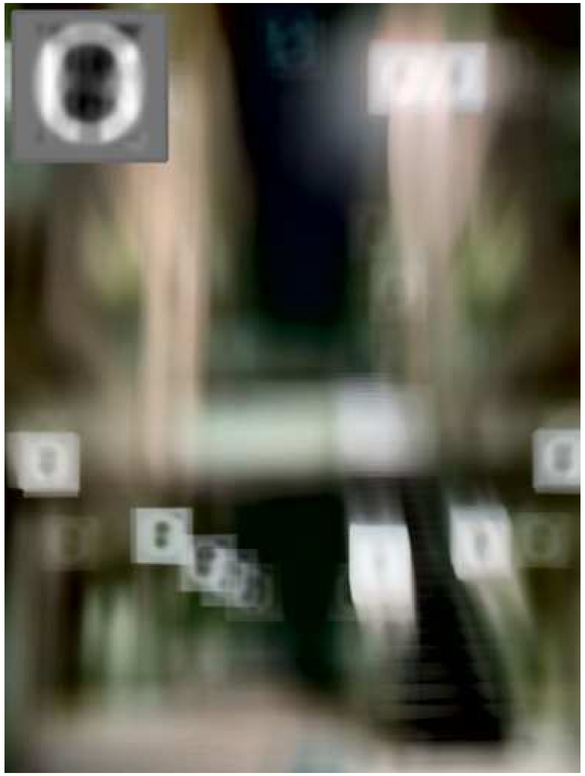
simulated PCA basis images

synthesized apertures

- Example of "*Bokeh Brush*" **post-capture stylization**, where the aperture function has been re-synthesized to represent each letter of the capitalized Arial font using a PCA-derived basis set

Vignetting Synthesis: Simulated Results

original HDR image



first PCA basis aperture

bokeh stylization

- Example of “*Bokeh Brush*” **post-capture stylization**, where the aperture function has been re-synthesized in a spatially-varying manner to read “BOKEH” along the left wall from a PCA basis set

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Conclusions and Future Work

Contributions

- ✓ Applied the fact that the out-of-focus image of a point light directly gives the point spread function – leading to a practical, low-cost method to simultaneously estimate vignetting and spatially-varying point spread function
- ✓ Introduced the *Bokeh Brush*: a novel, post-capture method for full-resolution control of the shape of out-of-focus points – achieved using a small set of images with varying basis aperture shapes

Limitations of the Calibration Procedure

- Point sources require long exposures and only provide sparse PSFs
- The point light source array is assumed to be uniform, but LCDs can vary

Limitation of the Bokeh Brush

- Can only reconstruct apertures well-approximated by chosen basis
- Achieves only modest compression ratios for included examples

Future Work

- Apply *Bokeh Brush* directly to light field photographs (i.e., pinhole basis set)