Computational Illumination

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Some Slides from Ramesh Raskar (MIT Medialab)
High level idea

• Control the illumination to
  – Lighting as a post-process
  – Extract more information
Flash/no-flash
Flash Photography Enhancement via Intrinsic Relighting

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Thursday, February 4, 2010
Introduction

Satisfactory photos in dark environments are challenging!
Introduction

Available light:
+ original lighting
- noise/blurriness
- color
Introduction

Flash:
+ details
+ color

- flat/artificial
- flash shadows
- red eyes
Introduction

Our approach:
Use no-flash image relight flash image

No-flash

Flash

Result

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Introduction

Our approach:
Use no-flash image relight flash image

+ original lighting
+ details/sharpness
+ color
Introduction

One approach: Blend the two photos

No-flash

Flash

Blending
Introduction

One approach: Blend the two photos

Blending

Our result
Introduction

One approach: Blend the two photos

Blending

Our result
Introduction

One approach: Blend the two photos
Introduction

One approach: Blend the two photos

Our Solution: more details and less noise

Blending

Our result
Overview

• Related Work
• Our Approach
• Results
• Conclusion and Future Work
Overview

• Related Work
• Our Approach
• Results
• Conclusion and Future Work
Related Work

Tone Mapping of High Dynamic Range Images
Decouple detail / large-scale information

- Tumblin et al. [1999]
- Durand et al. [2002]
- Choudhury et al. [2003]
Petschnigg et al. [2004]:

• many similarities
• part of this year’s proceedings
• discussion at the end
Overview

• Related Work
• Our Approach
• Results
• Conclusion and Future Work
Our Approach - Main Idea
Our Approach - Main Idea

no-flash

flash
Our Approach - Main Idea

no-flash → lighting → flash
Our Approach - Main Idea

no-flash

lighting

flash

color +
detail
Our Approach - Main Idea

- no-flash
- lighting
- flash
- color
- detail
- shadow treatment
Our Approach - Main Idea

- no-flash
- lighting
- result
- flash
- color
- detail
- shadow treatment
Our Approach

no-flash

flash
Our Approach

no-flash

flash

color

intensity
Our Approach
Our Approach
Our Approach

no-flash

flash
Our Approach

- *no-flash*
  - color
  - intensity
  - large scale

- *flash*
  - color
  - detail
  - large scale

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Our Approach

- **no-flash**
  - Color
  - Intensity
  - Large scale

- **flash**
  - Color
  - Intensity
  - Large scale

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Our Approach
Our Approach
Our Approach
Our Approach
Our Approach

no-flash → intensity → large scale → result

flash → color → detail

shadow treatment
Our Approach

Registration

no-flash

flash

result

shadow treatment

large scale

detail

intensity

color

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Registration

- Align to compensate for camera movement
- Difficult because lighting changes
- Edge detection

- See also Ward[2004], Kang[2003]
Our Approach

Registration

no-flash

flash

result

shadow treatment

large scale

detail

intensity

color


color

intensity
Our Approach

Decomposition
Decomposition

Color / Intensity:

original
Decomposition

Color / Intensity:

original = intensity * color
Our Approach

Decomposition

no-flash

intensity

color

detail

result

large scale

shadow treatment

color

intensity

flash
Our Approach

Decoupling

no-flash

flash

result

large scale

detail

color

intensity

shadow treatment

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Decoupling

- Lighting: Large-scale Variation
- Texture: Small-scale Variation

Large-scale

Small-scale
Decoupling

- Lighting: Large-scale Variation
- Texture: Small-scale Variation

Large-scale

Small-scale

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Large-scale Layer

- Gaussian filter

\[ I'(p) := \sum_{q} I(q) \cdot f(p - q) \]
Large-scale Layer

- **Bilateral filter**
  - Smith and Brady 97
  - Tomasi & Manducci 98

\[
I'(p) := \sum_{q} \left( I(q) \cdot f(p - q) \cdot g(I(p) - I(q)) \right)
\]
Large-scale Layer

- **Bilateral filter**
  - Smith and Brady 97
  - Tomasi & Manducci 98

\[ I'(p) := \sum_q I(q) f(p - q) g(I(p) - I(q)) \]
Large-scale Layer

- **Bilateral filter**
  - Smith and Brady 97
  - Tomasi & Manducci 98

\[ I'(p) := \sum_{q} I(q) \]

\[ f(p - q) g(I(p) - I(q)) \]
Large-scale Layer

- **Bilateral filter**
  - Smith and Brady 97
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\[ I'(p) := \sum_q I(q) f(p - q) g(I(p) - I(q)) \]
Large-scale Layer

• Bilateral filter
Large-scale Layer

• Cross Bilateral filter
  • Better smoothing for no-flash
  • Value penalization based on flash image
    ➢ edge stopping from flash image
Detail Layer

Intensity / Large-scale = Detail

Recombination: Large scale * Detail = Intensity
Recombination

Large-scale No-flash * Detail Flash = Intensity

Recombination: Large scale * Detail = Intensity
Recombination: Intensity * Color = Original
Our Approach

no-flash

intensity

color

detail

large scale

result

flash

intensity

color

detail

large scale

shadow treatment
Our Approach

Shadow Detection/Treatment

Diagram showing the process of detecting and treating shadows in images.

- no-flash phase
- flash phase
- color analysis
- intensity analysis
- detail analysis
- large scale analysis
- result
- shadow treatment
Problem

No correction
Shadow Correction – Why?

Global white balance in shadows
Shadow Correction – Why?

Several artifacts:
Shadow Correction – Why?

Several artifacts:
• at shadow boundary

Global white balance in shadows
Shadow Correction – Why?

Global white balance in shadows

Several artifacts:
• at shadow boundary
• inside shadows (color bleeding)
Shadow Correction – Why?

Global white balance in shadows

Several artifacts:
• at shadow boundary
• inside shadows (color bleeding)

➢ shadows need to be corrected!
Shadow Correction – Why?

Global white balance in shadows

Several artifacts:
• at shadow boundary
• inside shadows (color bleeding)

➤ shadows need to be corrected!

... and detected
Shadow Detection

Flash
Shadow Detection

Flash
Shadow Detection

• Umbra
Shadow Detection

- Umbra
- Penumbra
Shadow Detection

- Umbra
- Penumbra

➤ Detection in two steps
Shadow Detection
Shadow Detection

Umbra detection
Shadow Detection

Umbra detection

• uniform, scattered light from flash
Shadow Detection

Umbra detection

- uniform, scattered light from flash

- Difference of the two photos $\Delta I$ reveals these regions
Shadow Detection

Umbra detection

- uniform, scattered light from flash

Difference of the two photos $\Delta I$ reveals these regions
Shadow Detection

Umbra detection

• Difference $\Delta I = \text{light added by the flash}$

• Goal: Find a threshold for $\Delta I$
Shadow Detection

Umbra detection

➢ Umbra Detection Threshold
  (details in paper)
Shadow Detection

Umbra detection

- Umbra Detection Threshold
  (details in paper)
Shadow Detection

Umbra detection

- Umbra Detection Threshold
  (details in paper)
Shadow Detection

Umbra detection

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Shadow Detection

Umbra detection

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Umbra detection

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Umbra detection

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  (details in paper)
Shadow Detection

Umbra detection

- Umbra Detection Threshold
  (details in paper)
Shadow Detection

Umbra detection

- Umbra Detection Threshold (details in paper)
Shadow Detection
Shadow Detection

No-flash flash
Shadow Detection

Penumbra detection

- strong gradient at boundary
- no strong gradient in no-flash image
- connected to umbra

No-flash  flash
Shadow Detection

Penumbra detection

➢ **strong gradient at boundary**
• **no strong gradient in no-flash image**
• **connected to umbra**
Shadow Detection

Penumbra detection

- strong gradient at boundary
- no strong gradient in no-flash image
- connected to umbra

No-flash  flash  Umbra  Penumbra
Shadow Correction

- Need a **robust correction**
- Correct **color** and **detail**
Shadow Color Correction

Flash color
Shadow Color Correction

Flash color
Shadow Color Correction

Flash color

Wrong color
Shadow Color Correction

Flash color

Correct color

Wrong color
Shadow Color Correction

Flash color

Wrong color

Fill in shadow from similar surrounding

Correct color
Shadow Color Correction

Fill in shadow from similar surrounding

Flash color

Correct color

Wrong color
Shadow Color Correction

Flash color

Correct color

Wrong color

Fill in shadow from similar surrounding

No-flash colors
Shadow Color Correction
Shadow Color Correction
# Shadow Color Correction

<table>
<thead>
<tr>
<th>No-flash</th>
<th>Flash</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="No-flash Image" /></td>
<td><img src="image2.png" alt="Flash Image" /></td>
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*Thursday, February 4, 2010*
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Shadow Color Correction

No-flash

Flash
Shadow Color Correction

No-flash

Flash

Steve, February 4, 2010
Shadow Color Correction

No-flash

Flash

Outside shadow
Shadow Color Correction

No-flash

Flash

Inside shadow

Outside shadow
Shadow Color Correction

No-flash

Flash

Select pixel in shadow

Inside shadow

Outside shadow

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Shadow Color Correction

No-flash

Flash

Corresponding pixel

Inside shadow

Outside shadow
Shadow Color Correction

No-flash

Flash

Inside shadow

Outside shadow

Spatial weights
Shadow Color Correction

No-flash

Flash

Spatial and Color weights

Inside shadow

Outside shadow
Shadow Color Correction

No-flash

Flash

Spatial and Color weights
Shadow Color Correction

No-flash

Flash

Inside shadow

Outside shadow

Spatial and Color weights

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Shadow Color Correction

No-flash

Flash

Use shadow mask

Inside shadow  Outside shadow

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Shadow Color Correction

No-flash

Flash

Inside shadow

Outside shadow

Use shadow mask

Thursday, February 4, 2010
Shadow Color Correction

No-flash

Flash

Inside shadow

Outside shadow

Use shadow mask
Shadow Color Correction

No-flash

Flash

Use shadow mask

Inside shadow  Outside shadow
Shadow Color Correction

No-flash

Flash

Use shadow mask
Shadow Color Correction

No-flash

Flash

Use shadow mask

Inside shadow

Outside shadow
Shadow Color Correction

No-flash

Flash

Use shadow mask

Inside shadow

Outside shadow
Shadow Color Correction

No-flash

Flash

Use weights on flash color

Inside shadow

Outside shadow
Shadow Color Correction

No-flash

Flash

Inside shadow

Outside shadow

Replace shadow pixel
Shadow Color Correction

No-flash

Flash

Proceed for all shadow pixels
Shadow Color Correction

No-flash

Flash

Inside shadow
Outside shadow

Proceed for all shadow pixels
Our Approach
Our Approach

no-flash

result

flash

shadow treatment
Overview

• Related Work
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Results

No-flash

Flash
Results

No-flash

Flash
Results

No correction

Our result
Results

No-flash

Flash
Results

No-flash

Flash
Results

No-flash

Flash
Results

No-flash

Flash
Results

No-flash

Flash
Results

No-flash

Flash
Results

No-flash

Flash

Our result
Results

Our result
Results

Our result
Results

Our result
Results

Deduce “distance“ to camera

Exploit $1/r^2$ flash intensity falloff
Results

Deduce “distance“ to camera

Exploit $1/r^2$ flash intensity falloff

Emphasized foreground

Our result
Results

No-flash

(Inverse) White balance to original illumination

Flash
Results

(Inverse) White balance to original illumination
Results

No-flash

(IInverse) White balance to original illumination

Flash
Results

(Inverse) White balance to original illumination
Results

No-flash

Flash
Results

No-flash

Flash
Overview

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Improving photography in dim environments

- Capture original lighting
- Add sharpness/details
- Correct flash shadows
- Pseudo distance (emphasize foreground)
- white balancing
- Cross Bilateral Filter
Non-photorealistic Camera: Depth Edge Detection and Stylized Rendering using Multi-Flash Imaging

Ramesh Raskar, Karhan Tan, Rogerio Feris, Jingyi Yu, Matthew Turk
Mitsubishi Electric Research Labs (MERL), Cambridge, MA
Depth Edge Camera
Our method captures shape edges...
Canny Intensity Edge Detection

Our Method

Canny Intensity Edge Detection
Shadows
Clutter
Many Colors

Highlight Shape Edges
Mark moving parts
Basic colors
Flash matting
Flash Matting

Jian Sun\textsuperscript{1} \quad Yin Li\textsuperscript{1} \quad Sing Bing Kang\textsuperscript{2} \quad Heung-Yeung Shum\textsuperscript{1}

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Figure 1: Flash matting results for flower scene with complex foreground and background color distributions. From left to right: flash image, no-flash image, recovered alpha matte, and flower basket with new background.
Figure 4: Continuous shot. Top: flash/no-flash pair. Middle: Bayesian matting results on the flash and no-flash images (separate estimation). Bottom: Joint Bayesian flash matting result.
Relighting
Performance Relighting and Reflectance Transformation with Time-Multiplexed Illumination

SIGGRAPH 2005 Papers Proceedings

Andreas Wenger  Andrew Gardner  Chris Tchou
Jonas Unger  Tim Hawkins  Paul Debevec

University of Southern California Institute for Creative Technologies
Figure 5: Successive images of an actor lit by the 180-pattern sequence in the span of one twelfth of a second. Tracking and matte frames seen in the two left columns occur ten times each within the lighting basis with an effective rate of 120Hz in the 2160fps sequence.
Figure 4: Six elements of each of the three lighting bases used in this work. Top Row: Single lights. Middle Row: Triangles. Bottom Row: Hadamard Patterns
Figure 7: **Motion Compensation Process.** To compensate for the subject motion, basis frames (blue) are warped to match the target output frame (red). Optical flow is calculated between adjacent tracking frames (yellow), and linearly interpolated to warp each basis frame to the nearest tracking frame (black arrows) in the direction of the target output frame. Then, long-range warps (red arrows) are applied to bring each basis frame into alignment with the output frame.
Figure 8: (a) Relit frame without motion compensation, showing smearing. (b) Color-coded optical flow field computed between neighboring tracking frames. (c) Stabilized frame where motion compensation has been applied to the basis. (d) Relit frame with synthesized 180-degree shutter motion blur based on the flow field.
Figure 9: Reflectance Estimation and Transformation
(a) An original photographed image from the performance with the triangle basis.
(b) Estimated surface normals from the full lighting basis
(c) Estimated diffuse albedo.
(d) Estimated ambient occlusion.
(e) Original reflectance re-illuminated by an environment.
(f) Diffuse albedo with normals and occlusion illuminated by the environment.
(g) Specular reflection in the environment.
(h) Specular enhancement.
(i) Stylized plastic reflectance with occlusion.
(j) Diffuse reflectance with occlusion.
(k) Metallic specular reflectance.
(l) Diffuse reflectance without occlusion, yielding a translucent appearance.
Dual photography
To appear in the ACM SIGGRAPH 2005 conference proceedings

Dual Photography

Pradeep Sen*  Billy Chen*  Gaurav Garg*  Stephen R. Marschner†
Mark Horowitz*  Marc Levoy*  Hendrik P. A. Lensch*

*Stanford University  †Cornell University

Figure 1: (a) Conventional photograph of a scene, illuminated by a projector with all its pixels turned on. (b) After measuring the light transport between the projector and the camera using structured illumination, our technique is able to synthesize a photorealistic image from the point of view of the projector. This image has the resolution of the projector and is illuminated by a light source at the position of the camera. The technique can capture subtle illumination effects such as caustics and self-shadowing. Note, for example, how the glass bottle in the primal image (a) appears as the caustic in the dual image (b) and vice-versa. Because we have determined the complete light transport between the projector and camera, it is easy to relight the dual image using a synthetic light source (c) or a light modified by a matte captured later by the same camera (d).
Figure 2: The principle of dual photography. The top diagram shows our primal configuration, with light being emitted by a real projector and captured by a real camera. Matrix $T$ describes the light transport between the projector and the camera (element $T_{ij}$ is the transport coefficient from projector pixel $j$ to camera pixel $i$). The bottom diagram shows the dual configuration, with the positions of the projector and camera reversed. Suppose $T''$ is the transport matrix in this dual configuration, so that $T''_{ji}$ is the transport between pixel $i$ of the virtual projector and pixel $j$ of the virtual camera. As shown in Appendix A, Helmholtz reciprocity specifies that the pixel-to-pixel transport is equal in both directions, i.e., $T''_{ji} = T_{ij}$, which means $T'' = T^T$. As explained in the text, given $T$, we can use $T^T$ to synthesize the images that would be acquired in the dual configuration.
Figure 4: Photography without an imaging sensor. This image was generated using a projector and two photo-resistors like the one shown in the inset. This is a dual image of the scene in Figure 1 and is a view of the scene from the projector’s location as illuminated by point light sources at the locations of the two photo-resistors.
Figure 8: Sample scenes. The acquired primal image is on the left, the synthesized dual on the right. Note for example the detail on the pillar in the dual image of the bottom row which is barely visible in the primal due to foreshortening.
Figure 15: Using a mirror array to emulate multiple virtual projectors. (a) A camera was imaged onto the mirror array in order to emulate multiple virtual light positions. A block pattern scan consisting of 144 high dynamic range images was performed to acquire the scene’s transport matrix. The region of interest within the projector’s field of view was $864 \times 604$ pixels, the final resolution of the dual image. Each camera in the mirror array had an approximate resolution of $800 \times 600$ pixels, which is the resulting spatial resolution of our virtual lights. (b) The scene is illuminated by 12 point light sources to create soft shadows. (c) An animated character is embedded in the scene and casts shadows onto the scene.
Figure 16: Dual photography with indirect light transport. (a) A projector illuminates the front of a playing card while the camera sees only the back of the card and the diffuse page of the book. An aperture in front of the projector limits the illumination only onto the card. The card was adjusted so that its specular lobe from the projector did not land on the book. Thus, the only light that reached the camera underwent a diffuse bounce at the card and another at the book. (b) Complete camera view under room lighting. The back of the card and the page of the book are visible. It seems impossible to determine the identity of the card from this point of view simply by varying the incident illumination. To acquire the transport matrix, a $3 \times 3$ white pixel was scanned by the projector and 5742 images were acquired to produce a dual image of resolution $66 \times 87$. (c) Sample images acquired when the projector scanned the indicated points on the card. The dark level has been subtracted and the images gamma-corrected to amplify the contrast. We see that the diffuse reflection changes depending on the color of the card at the point of illumination. After acquiring the $T$ matrix in this manner, we can reconstruct the floodlit dual image (d). It shows the playing card from the perspective of the projector being indirectly lit by the camera. No contrast enhancement has been applied. Note that the resulting image has been automatically antialiased over the area of each projector pixel.
Separation of global/direct
Fast Separation of Direct and Global Components of a Scene using High Frequency Illumination

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Columbia University

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Columbia University

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City University of New York

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MERL

(a) Scene  (b) Direct Component  (c) Global Component

Figure 1: (a) A scene lit by a single source of light. The scene includes a wide variety of physical phenomena that produce complex global illumination effects. We present several methods for separating the (b) direct and (c) global illumination components of the scene using high frequency illumination. In this example, the components were estimated by shifting a single checkerboard pattern 25 times to overcome the optical and resolution limits of the source (projector) and sensor (camera). The direct and global images have been brightness scaled by a factor of 1.25. In theory, the separation can be done using just 2 images. When the separation results are only needed at a resolution that is lower than those of the source and sensor, the separation can be done with a single image.
Figure 5: (a) The steps involved in the computation of direct and global images using a set of shifted checkerboard illumination patterns. (b) The line occluder (stick) used to scan scenes lit by a simple source such as the sun. (c) The mesh occluder used to expedite the scanning process. (d) Three shifted versions of this sinusoid-based illumination pattern are sufficient to perform the separation. (e) A magnified part of the face image in Figure 7(d) reveals the stripe pattern used to do the separation from a single image.
Scene

(a) Eggs: Diffuse Interreflections

Direct Component

(b) Wooden Blocks: Diffuse and Specular Interreflections

Global Component

(c) Peppers: Subsurface Scattering
(d) Grapes and Cheese: Subsurface Scattering

(e) Kitchen Sink with Milky Water: Volumetric Scattering

(f) Novel Images
References