Computational Illumination

Course WebPage:
http://www.merl.com/people/raskar/photo/

Ramesh Raskar
Mitsubishi Electric Research Labs
Traditional ‘film-like’ Photography

Diagram:
- Lens
- Detector
- Pixels
- Image
Computational Photography: Optics, Sensors and Computations

Generalized Sensor

Computations

Ray Reconstruction

Upto 4D Ray Sampler

Picture

Generalized Optics

4D Ray Bender
Computational Photography

Novel Cameras

Generalized Sensor

Processing

Generalized Optics

Novel Illumination

Light Sources

[Image of wine bottle, cheese, and fruits]
Computational Photography

Novel Cameras

Generalized Sensor

Processing

Generalized Optics

Scene: 8D Ray Modulator
Computational Photography

Novel Illumination

Light Sources

Novel Cameras

Generalized Sensor

Processing

Generalized Optics

Display

Recreate 4D Lightfield

Scene: 8D Ray Modulator
**Computational Photography**

**Novel Cameras**
- Generalized Sensor
- Processing
  - Ray Reconstruction
  - Upto 4D Ray Sampler
- Generalized Optics
- 4D Ray Bender
- Display
  - Recreate 4D Lightfield

**Novel Illumination**
- Light Sources
- Modulators
- Generalized Optics
- 4D Incident Lighting
- 4D Light Field
- Scene: 8D Ray Modulator
Computational Illumination

Novel Cameras

Generalized Sensor
- Processing
  - Ray Reconstruction
  - Upto 4D Ray Sampler

Generalized Optics
- 4D Ray Bender

Programmable 4D Illumination field + time + wavelength

4D Light Field
- Display
- Recreate 4D Lightfield

Scene: 8D Ray Modulator
‘Smarter’ Lighting Equipment

What Parameters Can We Change?
Edgerton 1930’s
Edgerton 1930’s

Stroboscope
(Electronic Flash)

Multi-flash sequential photography

Flash

Camera Exposure

Time
Computational Illumination:
Programmable 4D Illumination Field + Time + Wavelength

- Presence or Absence, Duration, Brightness
  - Flash/No-flash
- Light position
  - Multi-flash for depth edges
  - Programmable dome (image re-lighting and matting)
- Light color/wavelength

- Spatial Modulation
  - Synthetic Aperture Illumination
- Temporal Modulation
  - TV remote, Motion Tracking, Sony ID-cam, RFIG
- Exploiting (uncontrolled) natural lighting condition
  - Day/Night Fusion
Computational Illumination

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Denoising Challenging Images

Available light:
+ nice lighting
- noise/blurriness
- color

No-flash
Flash:
+ details
+ color

- flat/artificial
Denoise no-flash image using flash image
Transfer detail from flash image to no-flash image

+ original lighting
+ details/sharpness
+ color
Cross-Bilateral Filter based Approach
Cross Bilateral Filter

- When no-flash image is too noisy
- Borrow similarity from flash image
  - edge stopping from flash image
Recombination: Large scale * Detail = Intensity
Need flash component!
Build Exposure HDR image

- Multiple images with different exposure
  - Debevec & Malik, Siggraph 97
  - Nayar & Mitsunaga, CVPR 00
Build Flash HDR image
Flash-Exposure Sampling

Build Flash-Exposure HDR image

Agrawal, Raskar, Nayar, Li
Siggraph05
Capturing HDR Image

- Varying Exposure time
- Varying Flash brightness
- Varying both
Flash and Ambient Images

[ Agrawal, Raskar, Nayar, Li   Siggraph05 ]
Intensity Gradient Vector Projection
Intensity Gradient Vectors in Flash and Ambient Images

Same gradient vector direction

Flash Gradient Vector

Ambient Gradient Vector

Ambient

Flash

No reflections
Different gradient vector direction

With reflections
Residual Gradient Vector

Intensity Gradient Vector Projection

Reflection Ambient Gradient Vector

Residual Gradient Vector

Flash Gradient Vector

Result Gradient Vector

Ambient

Flash

Result

Residual
<table>
<thead>
<tr>
<th>Ambient</th>
<th>Flash</th>
<th>Projection = Result</th>
<th>Residual = Reflection Layer</th>
</tr>
</thead>
</table>

Co-located Artifacts
Computational Illumination

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Synthetic Lighting
Paul Haeberli, Jan 1992
Debevec et al. 2002: ‘Light Stage 3’
Image-Based Actual Re-lighting

Debevec et al., SIGG2001

Film the background in Milan,
Measure incoming light,

Matched LA and Milan lighting.

Light the actress in Los Angeles

Matte the background
Photomontage

courtesy of A Agrawala

courtesy of P. Debevec

Ramesh Raskar, Computational Illumination
Table-top Computed Lighting for Practical Digital Photography

Ankit Mohan, Jack Tumblin
Northwestern University

Bobby Bodenheimer
Vanderbilt University

Cindy Grimm, Reynold Bailey
Washington University in St. Louis
Make this darker

Remove this specular highlight

Soften this shadow

Make this brighter

Move shadow back
Sketch Your Desires, Optimize
Acquisition for Relighting

- Uniquely lit basis images
- Known light-positions
‘Aimed Spot’: low-risk movement

Diffuse reflective enclosure

Camera

Object

Aimable light

Ramesh Raskar, Computational Illumination
Overlapped Spots avoid aliasing
“Light Waving”
Tech Sketch (Winnemoller, Mohan, Tumblin, Gooch)
Light Waving: Estimating Light Positions From Photographs Alone

Holger Winnemöller, Ankit Mohan, Jack Tumblin, Bruce Gooch
Northwestern University
Computational Illumination

Quest for 4D Illumination

Novel Cameras

- Generalized Sensor
- Generalized Optics
- 4D Ray Bender
- Upto 4D Ray Sampler
- Ray Reconstruction
- Display
- 4D Light Field
- Programmable 4D Illumination field + time + wavelength
- Light Sources
- Modulators
- Generalized Optics

Scene: 8D Ray Modulator

Ramesh Raskar, Computational Illumination
A 4-D Light Source

[Debevec et al. 2000]

[Masselus et al. 2002]

[Masselus et al. 2003]

[Malzbender et al. 2002]

Ramesh Raskar, Computational Illumination
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
U of California at Santa Barbara
U of North Carolina at Chapel Hill
Depth Edge Camera
Depth Discontinuities

Internal and external
Shape boundaries, Occluding contour, Silhouettes
Depth Edges
Our method captures shape edges
Our Method
MultiFlash NPR Camera

Photo

Result

Our Method

Canny Intensity Edge Detection
Shadows
Clutter
Many Colors

Highlight Shape Edges
Mark moving parts
Basic colors
A New Problem

Shadows
Clutter
Many Colors

Highlight Edges
Mark moving parts
Basic colors
Computational Illumination

- **Presence or Absence**
  - Flash/No-flash
- **Light position**
  - Multi-flash for depth edges
  - Programmable dome (image re-lighting and matting)
- **Light color/wavelength**

- **Spatial Modulation (Intra-flash 2D Modulation)**
  - Synthetic Aperture Illumination
- **Temporal Modulation**
  - TV remote, Motion Tracking, Sony ID-cam, RFIG
- **General lighting condition**
  - Day/Night
6-D Methods and beyond...

Relighting with 4D Incident Light Fields Vincent Masselus, Pieter Peers, Philip Dutre and Yves D. Willems SIGG2003
Synthetic Aperture Illumination: Comparison with Long-range synthetic aperture photography

- width of aperture 6’
- number of cameras 45
- spacing between cameras 5”
- camera’s field of view 4.5°
The scene

- distance to occluder  110’
- distance to targets  125’
- field of view at target 10’
Synthetic aperture photography using an array of mirrors

- 11-megapixel camera (4064 x 2047 pixels)
- 18 x 12 inch effective aperture, 9 feet to scene
- 22 mirrors, tilted inwards → 22 views, each 750 x 500 pixels
Synthetic aperture illumination

• technologies
  – array of projectors
  – array of microprojectors
  – single projector + array of mirrors
What does synthetic aperture illumination look like?
What are good patterns?

- (a) pseudo-random tiling
- (b) randomly permuted tiling
- (c) randomly placed tiles
- (d) sinuous patterns

pattern one trial 16 trials
Underwater confocal imaging with and without SAP
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Demodulating Cameras

- Motion Capture Cameras
  - Visualeyez™ VZ4000 Tracking System
  - PhaseSpace motion digitizer
**Cameras**
- 2 Detectors
- 460 Hz
- 3,600 x 3,600 Optical Resolution
- 30,000 x 30,000 Sub-Pixel Resolution

**64 Bit Processor PC**
- Camera Processing Software
  - Peak Tracking
  - Position, Velocity, Acceleration
  - Marker Identification
  - Filtering
- 3D Point Calculation
  - 3D Point Tracking
  - Occluded Point Interpolation
  - Dynamic Camera Offset
- User Interface
  - Session Control
  - Real-time Viewing Software
- Client-Side Data Access
  - 3rd Party Plugins
  - Open API
Demodulating Cameras

- Decode signals from blinking LEDs + image
  - Sony ID Cam
  - Phoci
R F I G Lamps:
Interacting with a Self-describing World via Photosensing Wireless Tags and Projectors

Ramesh Raskar, Paul Beardsley, Jeroen van Baar, Yao Wang, Paul Dietz, Johnny Lee, Darren Leigh, Thomas Willwacher

Mitsubishi Electric Research Labs (MERL), Cambridge, MA
Radio Frequency Identification Tags (RFID)

No batteries, 
Small size, 
Cost few cents
Conventional Passive RFID

Diagram showing the components of a conventional passive RFID system:
- Memory
- Micro Controller
- Reader
- Computer

The diagram illustrates the interaction between these components in a conventional passive RFID system.
Tagged Books in a Library

✓ **Id**
Easy to get list of books in RF range

✗ **No Precise Location Data**
Difficult to find if the books in sorted order?
Which book is upside down?
Where are boxes with Products close to Expiry Date?
Photosensor?

Compatible with RFID size and power needs

Projector?

Directional transfer, AR with Image overlay
a. Photosensing RFID tags are queried via RF

b. Projector beams a time-varying pattern unique for each (x,y) pixel which is decoded by tags

c. Tags respond via RF, with date and precise (x,y) pixel location. Projector beams ‘O’ or ‘X’ at that location for visual feedback

d. Multiple users can simultaneously work from a distance without RF collision
RFID
(Radio Frequency Identification)

RFIG
(Radio Frequency Id and Geometry)
Prototype Tag

RF Transponder

Photo Sensor

Processor

RF tag + photosensor
Projected Sequential Frames

- Handheld Projector beams binary coded stripes
- Tags decode temporal code
Projected Sequential Frames

- Handheld Projector beams binary coded stripes
- Tags decode temporal code
Projected Sequential Frames

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Projected Sequential Frames

- Handheld Projector beams binary coded stripes
- Tags decode temporal code
For each tag
a. From light sequence, decode $x$ and $y$ coordinate
b. Transmit back to RF reader $(\text{Id}, x, y)$

X=12
Visual feedback of 2D position

a. Receive via RF \{((x_1,y_1), (x_2,y_2), \ldots)\} pixels
b. Illuminate those positions
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A Night Time Scene:
Objects are Difficult to Understand due to Lack of Context
Enhanced Context:
All features from night scene are preserved, but background in clear.
Background is captured from day-time scene using the same fixed camera

Result: Enhanced Image
Mask is automatically computed from scene contrast
But, Simple Pixel Blending Creates Ugly Artifacts
Our Method:
Integration of blended Gradients
‘Smarter’ Lighting Equipment

Programmable Parameters
Computational Illumination

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Generalized Sensor

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