Radiometry and Appearance Models

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The Visual World

Rich variety of materials: characterized by surface reflectance, scattering

Understanding Reflectance

for each position:
  for each direction of incident light:
  for each reflected direction:
  how much light is reflected?

Understanding Scattering

for each incident position:
  for each exitant position:
  how much light is scattered?

Motivation

- Understanding appearance models aids in:
  - Photorealistic image synthesis
  - Image-based view and lighting interpolation
  - 3D reconstruction from images
  - Image interpretation
  - Understanding human material perception

Overview

- Radiometry and Radiometric Units
- BRDF properties and common BRDFs
- Subsurface scattering
- Taxonomy of reflection and scattering functions
**Radiometric Units**

- Light is a form of energy - measured in Joules (J)
- **Power**: energy per unit time
  - Measured in Joules/sec = Watts (W)
  - Also called Radiant Flux (\(\Phi\))

**Point Light in a Direction**

- Total radiant flux in Watts
- How to define angular dependence?
  - Solid angle

**Digression – Solid Angle**

- **Angle in radians**
  - \(\text{Length} / \text{Angle} = \theta / r\)

- **Solid angle in steradians**
  - \(\text{Area} \cdot \text{Solid angle} = A \cdot \omega = A \cdot r^2\)

**Point Light in a Direction**

- Radiant flux per unit solid angle
  - Measured in Watts per steradian (W/sr)

**Light Falling on a Surface**

- **Power per unit area - Irradiance (E)**
  - Measured in \(\text{W/m}^2\)

- Move surface away from light
  - Inverse square law: \(E \sim 1/r^2\)

- **Tilt surface away from light**
  - Cosine law: \(E \sim \mathbf{n} \cdot I\)

**Light Emitted from a Surface in a Direction**

- **Power per unit area per unit solid angle - Radiance (L)**
  - Measured in \(\text{W/m}^2/\text{sr}\)
  - *Projected area* - perpendicular to given direction

  \[
  L = \frac{d\Phi}{dA \, d\omega}
  \]

  - Cameras (and our eyes) "see" radiance
Surface Reflectance – BRDF

• Bidirectional Reflectance Distribution Function
  \[ f_r(\omega_i \rightarrow \omega_o) = \frac{dL_o(\omega_o)}{dE_i(\omega_i)} \]

• 4-dimensional function: also written as
  \[ f_r(\theta_i, \phi_i, \theta_o, \phi_o) = \frac{dL_o(\omega_o)}{dE_i(\omega_i)} \]


BRDF

• Radiance/irradiance ratio
  – Directional exitant radiance distribution
  – For each direction of incident irradiance

Isotropy

• A BRDF is isotropic if it stays the same when surface is rotated around normal

• Isotropic BRDFs are 3-dimensional functions:
  \[ f_r(\theta_i, \theta_o, \phi_i - \phi_o) \]

Properties of the BRDF

• Energy conservation:
  \[ \int_{\Omega} f_r \cos \theta_o \, d\omega_o \leq 1 \]

• Helmholtz reciprocity:
  \[ f_r(\omega_i \rightarrow \omega_o) = f_r(\omega_o \rightarrow \omega_i) \]
**Anisotropy**

- Anisotropic BRDFs do depend on surface rotation

**Other BRDF Features**

- BRDFs for dusty surfaces scatter light towards grazing angles

**Other BRDF Features**

- Retroreflection: strong reflection back towards the light source
- Can arise from bumpy diffuse surfaces
- ... or from corner reflectors

**Lambertian BRDF**

- Constant BRDF: ideal diffuse reflectance

\[ f_r = \text{const.} = \frac{\rho}{\pi} \]

**Blinn-Phong BRDF**

- Simple BRDF describing specular reflection

\[ f_r = \frac{\rho}{\pi} + k_s (n \cdot h)^a \]

**Torrance-Sparrow BRDF**

- Physically-based BRDF model
  - Originally used in the physics community
  \[ f_r = \frac{DG F}{\pi \cos \theta_i \cos \theta_o} \]
  - Assume surface consists of tiny “microfacets” with mirror reflection off each
Torrance-Sparrow BRDF

- $D$ term is distribution of microfacets (i.e., how many are pointing in each direction)
- Beckmann distribution
  \[
  D = \frac{e^{-(\tan \beta/m)^2}}{4m^2 \cos^4 \beta}
  \]
  - $\beta$ is angle between $n$ and $h$
  - $h$ is halfway between $l$ and $v$
  - $m$ is "roughness" parameter

$G$ term accounts for self-shadowing

\[
G = \min \left\{ 1, \frac{2(n \cdot h)(n \cdot v)}{(v \cdot h)} \frac{2(n \cdot h)(n \cdot l)}{(v \cdot h)} \right\}
\]

Torrance-Sparrow BRDF

- $F$ is Fresnel term - reflection from an ideal smooth surface (solution of Maxwell’s equations)
- Consequence: most surfaces reflect (much) more strongly near grazing angles

Complex BRDF Models

- Analytic
  - Red Rubber
  - Lunar Dust
  - Obsidian
  - Tungsten
  - Bronze
  - Olive Drab
  - Copper
  - Tin
  - Nickel

- Measured
  - [COOK & TORRANCE 1982]
  - [MATUSIK ET AL. 2003]

The SVBRDF: 6D

- Spatially Varying
- Bi-Directional
- Reflectance Distribution Function

Bidirectional Texture Functions

- For non-flat samples, datasets include effects due to occlusion, shadowing
  - Often called Bidirectional Texture Functions - BTFs

[DANA ET AL. 1999]
Translucent Materials

Surface reflection only
With subsurface scattering

Subsurface Scattering

- Translucency: light no longer leaves surface at point of incidence
  - Not a BRDF!

The BSSRDF

- The Bidirectional Scattering-Surface Reflection Distribution Function
  \[ S(x_i, y_i, \theta_i, \phi_i, x_o, y_o, \theta_o, \phi_o) \]
  - Generalization of spatially-varying BRDF

BSSRDF Simplification

- BSSRDF often dominated by multiple scattering
- Accurately modeled by diffusion approximation
  \[ S = F(\theta_i) R(|| x_i - x_o ||) F'(\theta_o) \]
  - Angular behavior described by Fresnel equations
  - Spatial behavior equivalent to a dipole

BSSRDF Dipole Model

Surface reflection only
With subsurface scattering

BSSRDF: Homogeneous

- Homogeneous: uniform material
BSSRDF: Heterogeneous

- Homogeneous: uniform material
- Heterogeneous: spatially-varying materials

Generalizing Further

- Many additional effects could be incorporated into appearance functions: add 1 dimension for each
  - Wavelength
  - Fluorescence
  - Time dependence
  - Phosphorescence

Appearance Taxonomy

Scattering function: 12D
  \((x, y, \theta, \phi, \lambda_x, \lambda_y, \alpha, \beta, \gamma)\)

BSSRDF: 8D
  \((x, y, \theta, \phi, \lambda_x, \lambda_y, \alpha, \beta)\)

SVBRDF: 6D
  \((x, \theta, \phi, \lambda_x, \lambda_y, \alpha)\)

BRDF: 4D
  \((\theta, \phi)\)

Isotropic BRDF: 3D
  \((\theta, \phi)\)

Heterogeneous Multiple Scattering: 4D
  \((x, y, \theta, \phi, \lambda_x, \lambda_y)\)

Homogeneous Multiple Scattering: 1D
  \(||\lambda_x - \lambda_y||\)

Diffuse Texture: 2D
  \((\theta, \phi)\)

Rest of This Tutorial

- A Review of Radiometry & Physical Models – Rusinkiewicz
- Principles of Acquisition – Zickler
- (Spatially Varying) BRDF Models – Lawrence
- From BSSRDFs to 8D Reflectance Fields – Lensch
- The Human Face Scanner Project – Weyrich
- Future Directions / Q&A
Principles of Acquisition

Todd Zickler
Harvard University

Outline

1. 5D: Homogeneous Reflectance (BRDF)
2. 7D: Spatially-varying Reflectance (SV-BRDF)
3. 9D: Subsurface Scattering (BSSRDF)
4. Calibration
5. Open problems

Balancing Needs

1. (Per-object) Acquisition Time
2. Accuracy and Precision
3. Cost
4. Generality: how broad is the class of surfaces being considered?

Homogeneous Reflectance

- BRDF: Five dimensional domain
  \[ f(\lambda, \hat{\omega}_i, \hat{\omega}_o) = f(\lambda, \theta_i, \phi_i, \theta_o, \phi_o) \]
- Isotropic BRDF: Four dimensional domain
  \[ f(\lambda, \theta_i, \theta_o, |\phi_i - \phi_o|) \]

BRDF: Measurement Scale

- One measures *averages* of the BRDF over finite intervals of surface area and solid angle.
- The measurement scale must be appropriate for the BRDF model to be valid (more on this later).

The Gonioreflectometer

Four-axis gonioreflectometer

[White et al., 1998]
The Gonioreflectometer

Three-axis gonioreflectometer

- Isotropic BRDF
- 1000 angular samples
- 31 spectral samples
- 10 hours per BRDF

Image-based measurement: planar

- Camera: Observe multiple output angles simultaneously
- Trade precision (and accuracy?) for efficiency

Image-based measurement: curved

Image-based measurement: general

[Li et al., 2005]

[Ward, 1992]

[Ghosh et al., 2007]

[Marschner, 1998; Lu et al., 1998]

[Matusik et al., 2003]

[http://www.merl.com/brdf/]

[Regan et al., 2009]

[Marschner et al., 1999]
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**Spatially-varying Reflectance**

- **SV-BRDF:** Seven dimensional domain
  \[ f(\lambda, \vec{x}, \vec{\omega}_i, \vec{\omega}_o) = f(\lambda, x, y, \theta_i, \phi_i, \theta_o, \phi_o) \]
- **Isotropic SV-BRDF:** Six dimensional domain
  \[ f(\lambda, x, y, \theta_i, \theta_o, |\phi_i - \phi_o|) \]

**Planar Surfaces:**

**The Spatial Gonioreflectometer**

Three-axis spatial gonioreflectometer

[Image: Dana et al., 1997; McAlistier, 2002]

**Planar Surfaces:**

**Another Spatial Gonioreflectometer**

- Can use catadioptrics to re-sort light rays and exchange spatial and angular resolution.

[Image: Dana et al., 2004]

**Planar Surfaces:**

**Another Spatial Gonioreflectometer**

- Can use catadioptrics to re-sort light rays and exchange spatial and angular resolution.

[Image: Dana et al., 2004]

**Curved Surfaces**

- Many interesting surfaces are not planar.
- Non-planar shapes can be used, provided the shape is known.

[Image: Stanford Spherical Gallery (also Cornell, UVA, UCSD...)]
Counting Images

Reduce acquisition time by:
1. Designing efficient acquisition systems
2. Using parametric BRDF models
3. Exploiting common reflectance phenomena

Parametric Approaches

- Pro: requires estimating only a handful of parameters at each surface point.
- Con: requires choice of specific parametric family (Oren-Nayar, Cook-Torrance, Phong,...)

\[
f_x(\hat{i}, \hat{e}) \iff f_x(\hat{\alpha}; \hat{i}, \hat{e})
\]

General Reflectance Properties

- Isotropy: from a 6D domain to 5D
- Reciprocity: cuts the angular domain in half
- Compressibility: BRDF is slowly varying over much of its angular domain
- Separability: distinct diffuse and specular components
- Spatial smoothness: slow variation from point to point
- Spatial regularity: a common per-object BRDF basis

Parametric Approaches

- Some parametric approaches:
  - [Yu et al., 1999]
  - [Boivin, Gagalowicz, 2001]
  - [Lensch, et al., 2001]
  - [McAllister, Lastra, Heidrich, 2002]
  - [Georghiades, 2003]
  - [Goldman et al., 2005]
  - ...
General Reflectance Properties

- Isotropy, reciprocity, separability are commonly exploited
- Compressibility
  - Implicit in parametric approaches; used in non-parametric approaches as well
- Spatial smoothness
  - Exploited in parametric (e.g., [Sato, Wheeler, Ikeuchi, 1997]) and non-parametric (e.g., [Zickler et al., 2006]) approaches
- Spatial regularity
  - Exploited in parametric (e.g., [Lensch et al., 2001], [Goldman et al. 2005]) and non-parametric (e.g., [Lawrence et al., 2006]) approaches

Separability (Dichromatic Model)

\[ I_{RGB} = \hat{n} \cdot \hat{i} D \]

\[ D_k = \int E(\lambda) R(\lambda) C_k(\lambda) d\lambda \]

[Shafer, 1985]

Separability (Dichromatic Model)

\[ I_{RGB} = \hat{n} \cdot \hat{i} D + f(\hat{n}, \hat{i}, \hat{v}) S \]

\[ D_k = \int E(\lambda) R(\lambda) C_k(\lambda) d\lambda \]

\[ S_k = \int E(\lambda) C_k(\lambda) d\lambda \]

[Shafer, 1985]

“Separable” Materials

[Tominga and Wandell, 1989; Healey, 1989; Lee et al., 1990]

Implications for Acquisition

DIFFUSE

- Approx. Lambertian
- Rapid spatial variation
- Randomly polarized

SPECULAR

- Non-Lambertian
- Slow spatial variation
- Monochromatic
- Partially polarized
Example: Reflectance Sharing

Exploits:
- Separability
- Isotropy/Reciprocity
- Compressibility
- Slow spatial variation

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Subsurface Scattering

- BSSRDF:
  \[ S(\lambda, \vec{x}_i, \omega_i, \vec{x}_o, \omega_o) \]
- Homogeneous, multiple scattering:
  \[ F_t(\eta, \omega_i) R(\lambda, \|\vec{x}_i - \vec{x}_o\|) F_t(\eta, \omega_o) \]

BSSRDF

\[ F_t(\eta, \omega_i) R(\lambda, \|\vec{x}_i - \vec{x}_o\|) F_t(\eta, \omega_o) \]

[Zickler et al., 2006]

[Jensen et al., 2001]
**BSSRDF**

\[
S(\lambda, \vec{x}_i, \vec{\omega}_i, \vec{x}_o, \vec{\omega}_o) = f_i(\vec{\omega}_i) R_{id}(\vec{x}_i, \vec{x}_o) f_o(\vec{x}_o, \vec{\omega}_o)
\]

![Diagram of BSSRDF](image)

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**Radiometric Calibration**

- Camera:
  - Response function and high dynamic range (HDR) imaging

![Image of Radiometric Calibration](image)
Radiometric Calibration

- Camera:
  - Response function and high dynamic range (HDR)
  - Optical fall-off
  - Spectral filters

- Light source(s):
  - Temporal variation
  - Angular non-uniformity
  - Spectral power distribution

- Projector(s):
  - Optical fall-off
  - Spectral filters

Geometric Calibration

- Camera/projector parameters (intrinsic/extrinsic)
- Source direction
- Surface Shape. Ideally:
  - Surface normals (Photometric stereo; Helmholtz stereo)
  - Independent of reflectance
  - Same images used for shape and reflectance

Some Open Problems

- Automatic scale selection

[Debevec et al., 2007]

Some Open Problems

- Automatic scale selection

[Debevec et al., 2007]

[Nayar et al., 2006]
Some Open Problems

- Automatic scale selection
- Acquisition (inference) in complex lighting environments. [Dror 2001, Ramamoorthi and Hanrahan 2001]
- SV-BRDF acquisition as an inference problem. What are the priors?
- Increased spectral resolution
- Combined shape and reflectance acquisition
Spatially-Varying BRDF Models

Jason Lawrence
University of Virginia

A Spatially-Varying BRDF

$S(u, v, \omega_i, \omega_o)$

Talk Outline

- acquisition
- representations
- future directions

Acquisition
Outline

- acquisition
- representations
- future directions

Representation

- goals
  - compact
  - editable
  - sampling
- challenges
  - scattered data
  - dimensionality
  - massive datasets

Representation

- goals
  - compact
  - editable
  - sampling
- challenges
  - scattered data
  - dimensionality
  - massive datasets

Goal

- input: large set of reflectance measurements
- representation that is compact and editable

Strategy: Basis Decomposition

\[ S(u, v, \omega_i, \omega_o, \lambda) \approx \sum_{k=1}^{K} T_k(u, v) \rho_k(\omega_i, \omega_o, \lambda) \]
Strategy: Basis Decomposition

\[ S(u, v, \omega_i, \omega_o, \lambda) \approx \sum_{k=1}^{K} T_k(u, v) \rho_k(\omega_i, \omega_o, \lambda) \]

General Strategy

- parametric
  - fit parametric BRDF model
  - cluster
  - reproject onto basis
- non-parametric
  - tabulate the reflectance data
  - cast as matrix factorization
  - place constraints on factors

Acquisition

Lensch, H., Kautz, J., Goesele, M., Heidrich, W., Seidel, H.-P.
Image-Based Reconstruction Spatial Appearance
ACM Transactions on Graphics 22(3), 2003

Registration

silhouette-based alignment procedure

Fitting Lafortune Parameters

\[ \rho(\vec{r}, \vec{v}) = k_d + \sum_i |C_{x,i}(l_x v_z + l_y v_y) + C_{z,i} l_z v_z|^{N_i} \]

Clustering
Reprojection

Goldman et al. 2005

One input image
Normal map
Reconstruction
Blending weights + basis BRDFs (Ward)

Goldman, D., Curless, B., Hertzmann, A., Seitz, S.
Shape and Spatially Varying BRDFs from Photometric Stereo

General Strategy

- parametric
  - fit parametric BRDF model
  - cluster
  - reproject onto basis
- non-parametric
  - tabulate the reflectance data
  - cast as matrix factorization
  - place constraints on factors

Wallpaper Dataset

Inverse Shade Trees

Inverse Shade Tree Framework

Lawrence, J., Ben-Artzi, A., DeCoro, C., Matusik, W., Pfister, H., Ramamoorthi, R., Rushmeier, H.
Inverse Shade Tree Framework for Non-Parametric Material Representation and Editing
Inverse Shade Tree Framework

decomposition at each level is cast as matrix factorization

Tabulate Raw Data

Factor SBRDF
Research Challenge

providing an intuitive factorization:

\[ \begin{bmatrix} \hat{r}_1 & \hat{r}_2 & \cdots \end{bmatrix} = \begin{bmatrix} \tilde{r}_1 & \cdots \end{bmatrix} \begin{bmatrix} \hat{\lambda}_1 & \cdots \end{bmatrix} \]

Key Idea

incorporate domain-specific knowledge as constraints of factorization:

\[ \begin{bmatrix} \hat{r}_1 & \hat{r}_2 & \cdots \end{bmatrix} = \begin{bmatrix} \tilde{r}_1 & \cdots \end{bmatrix} \begin{bmatrix} \hat{\lambda}_1 & \cdots \end{bmatrix} \]

plausible BRDFs

plausible blending weights

Factorization Constraints

- non-negativity: reflectance functions are non-negative
- sparsity: few BRDFs at each position
- domain-specific:
  - energy conservation, monotonicity, etc.

Factorization Algorithms

<table>
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<th>algorithm</th>
<th>linear</th>
<th>positive</th>
<th>sparse</th>
<th>domain</th>
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</tbody>
</table>
Alternating Constrained LS

1. Initialize $W$ and $H$
2. Update $W$
3. Update $H$
4. Iterate until convergence

Reflectance Constraints

- non-negativity
  - constraint on value
- energy conservation
  - constraint on sum
- monotonicity
  - constraint on derivative

Measure of Sparsity

$$E_{\text{sparse}} = \sum_{i \neq j} w_i$$
$$w_j \geq w_i, \quad i = 1, \ldots, K$$

Season’s Greetings Dataset

5 Camera Positions x 350 Light Positions ~ 1,750 Images

Gold Foil Silver Foil White Paper Blue Paper
Season’s Greetings Dataset

Factorization Computed with ACLS (4 Terms)

Golden Foil  Silver Foil  White Paper  Blue Paper

Wood+Tape Dataset

12 Camera Positions x 480 Light Positions = 6,000 Images

Oak Wood (Anisotropic)  Semi-Transparent Tape  Retroreflective Bicycle Tape

Wood+Tape Dataset

Blending Weights from ACLS (5 Terms)

Scotch Tape  Dark Grain  Light Grain  Red Bicycle  White Bicycle

Wood+Tape Dataset

Blending Weights from ACLS (5 Terms)

SVD  0.014
NMF  0.015
K-means  0.029
ACLS  0.022

Wood+Tape Dataset

6D SVBRDF

2D blending weights  4D basis BRDFs

Wood+Tape Dataset

6D SVBRDF

2D blending weights  4D basis BRDFs
reparameterization and factorization

single-term factorization

specular highlight grazing effects

“lobes”

curves 1D

BRDF 4D

original

curves 1D

edits at leaf propagate up the tree

sharper

BRDF 4D

“lobes”

curves 1D

• representation goals:
  - compact
  - editable
  - supports rendering
• basis decomposition
  - parametric
  - non-parametric

Summary
Summary

• sparse/scattered data
• interpolation
• flexibility
• local minima

Summary

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Summary

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Summary

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• interpolation
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Future Directions

• higher-dimensional datasets
  – subsurface scattering / reflectance field
  – time-varying properties
  – etc.
• rigorous probabilistic framework
• measurement
  – synchronous shape + appearance
  – lowering calibration burden

Future Directions

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Future Directions

- higher-dimensional datasets
  - subsurface scattering / reflectance field
  - time-varying properties
  - etc.
- **rigorous probabilistic framework**
- measurement
  - synchronous shape + appearance
  - lowering calibration burden
From BSSRDFs to 8D Reflectance Fields

Hendrik P. A. Lensch
MPI Informatik

Digitizing Real World Objects
relighting with arbitrary illumination patterns

Relighting
one image for each light direction

Relighting
superposition

Reflectance Fields
[Debevec2000]
2D
arbitrary materials, but single view point

Reflectance Field – 6D
[Debevec2000]
arbitrary materials, arbitrary geometry
Bidirectional Texture Functions

arbitrary materials, surface patch

[Debevec2000]

arbitrary materials, but distant light sources only

6D Reflectance Fields

relighting with 4D incident light fields

[Masselus2003]

8D Reflectance Fields

arbitrary materials + arbitrary viewpoint + arbitrary illumination

[Sattler2003]

[Mueller2005]
Definition – Reflectance Field

$$f_r(\tilde{x}_i, \tilde{\omega}_i) \rightarrow (\tilde{x}_o, \tilde{\omega}_o)$$

Main Problem

- sampling an 8D function
  - spending 100 samples/dimension → 10^{16} samples
  - hi-res 3D geometry: 10^8 vertices

- coherence in reflectance fields → reduced data complexity

- no complete solution yet

Approaches

- limited reflectance model
- limited reproduction
  - viewer position
  - incident illumination
- adaptive parallel acquisition
- advanced interpolation

Relighting with 4D Incident Light Fields

- goal: relighting with spatially varying illumination, e.g. spot lights

Acquisition with Large Blocks

- fixed camera perspective
- rotating illumination
Relighting Results

Translucent Objects
- light transport through the object
- scattering dampens high frequencies

BSSRDF – 8D
bidirectional scattering-surface reflectance distribution function [Nico87]

\[ f_r((\vec{x}_l, \vec{\omega}_l)) \rightarrow (\vec{x}_o, \vec{\omega}_o) \]

\[ L_o(\vec{x}_o, \vec{\omega}_o) \]

\[ L_r(\vec{x}_r, \vec{\omega}_r) \]

Diffuse Approximation
neglect directional dependency [Jens01]
- multiple scattering leads to diffuse light transport

4D - Diffuse Approximation
⇒ diffuse reflectance function \( R_d(\vec{x}_l, \vec{x}_o) \)
- four dimensions only
- dense sampling is possible

\[ B(\vec{x}_o) \]

\[ E(\vec{x}_l) \]

Diffuse Reflectance Function \( R_d \)
- discretize the surface
  - enumerate all surface points
  - vectors for irradiance \( \vec{E} \) and radiosity \( \vec{B} \)
- matrix \( R_d \)
  - linear point-to-point transport

\[
\begin{bmatrix}
\vec{B}_i
\end{bmatrix} = \begin{bmatrix} R_d \end{bmatrix} \begin{bmatrix} \vec{E}_j \end{bmatrix}
\]
Basic Idea

- direct measurement of $R_d$
  - illuminate individual surface points
  - capture impulse response function

$B_j \Rightarrow [E_j]

Matrix Representation

- 500,000 - 1,000,000 input images
  $\Rightarrow \sim 100,000^2$ entries

- fill up holes (inpainting)
- hierarchical representation
- hardware assisted rendering
  - analysis
  - real-time rendering

[Lensch, Goesele, Bekaert, Magnor, Lang, Seidel – PG2003]
Video

1,000,000 images, 22 hours → model - 800MB

Fixed Perspective + Arbitrary Illumination

Adaptive Parallel Acquisition

- assumption: sparse matrix
- radiometrically independent blocks can be sensed in parallel

Adaptive Parallel Acquisition

parallelized acquisition of regions which do not overlap in the camera image
Relighting with Arbitrary Patterns

1,200 images. 2 hours → model - 220MB

Captured Global Light Transport

Helmholtz Reciprocity

dual

Image Acquisition without a Camera

primal

Image Acquisition without a Camera

camera
dual

Dual Photography

photograph from camera
dual image from projector

[Sen, Chen, Garg, Marschner, Horowitz, Levoy, Lensch - SIGGRAPH 2005]
Examples

- primal
- dual

Related Techniques

- “Flying-spot” TV camera [Baird 1926]
- scanning electron microscope

Relighting with Dual Photography

Acquisition of 6D Reflectance Fields

- active devices
- parallel acquisition by passive devices

Dual Acquisition Process
Smooth Interpolation

100,000 images, 26 hours → model - 4.5GB

[Chen, Lensch - VMV2005]

8D Reflectance Fields

arbitrary view point + arbitrary illumination

Φ-Matrices

[Hackbusch2000]

efficient representation of dense but data-sparse matrices
- subdivision hierarchy
- local low-rank approximation
- efficient evaluation

Direct vs. Indirect Reflections

Direct vs. Indirect Reflections

Direct vs. Indirect Reflections
2D Slices through a Reflectance Field

Symmetric Acquisition
- symmetric 8th order tensor
- rank-1 approximation from two images only
- parallel acquisition of dense matrices

Symmetric Exploration
- B3 – row sums
- B3T – columns
- B2 – rows + columns
- B1 – rows + columns

Symmetric Exploration
- B3 – row sums
- B3T – columns
- B2 – rows + columns
- B1 – rows + columns
- rank-1 approximation?

Hierarchical Rank-1 Decomposition
- B1 and B2 are investigated in parallel.
- parallel acquisition even for dense matrices

Dual vs. Symmetric Photography
- increased SNR because regions are determined at large block sizes
An 8D Reflectance Field

3.300 images, 6 hours → model - 1.4 GB

Virtual Photography

- reflectance fields of arbitrarily complex scenes


Application of Near-field Reflectance Fields

- getting rid of global effects

compare [Nayar2006]

Application to 3D Scanning

[Chen, Fuchs, Lensch, Seidel – CVPR 2007]

Card Experiment

book projector card

primal

Card Experiment

book virtual projector card

primal
Card Experiment

Near-Field Reflectance Fields
- Sequential Sampling
- Dual Photography
- Symmetric Photography based on $\mathcal{H}$-matrices
- First methods for acquiring the global light transport in arbitrary scenes

Challenges
- Densely sampled 8D reflectance fields
- Upsampling / interpolation
- Dynamic near-field reflectance fields
- Interactive relighting
- Global illumination with reflectance fields
- Theory on the complexity of reflectance fields

Thanks
- BMBF (FKC01IMC01)
- DFG - Emmy Noether Program

http://mpi-inf.mpg.de/~lensch
The Human Face Scanner Project

Tim Weyrich
Princeton University

Facial Appearance Acquisition

“Grand challenge” in appearance acquisition:
- Complex reflectance and scattering properties
- In vivo measurements required
- High expectation by the observer
- Appearance editing desirable

Analysis of Human Faces

Analysis of Human Faces
Using a Measurement-Based Skin Reflectance Model
[Weyrich et al. 2006]

joint work at
ETH Zurich, Switzerland,
and Mitsubishi Electric Research
Laboratories, Cambridge, MA

Objectives

- Capture facial appearance

Objectives

- Capture facial appearance
- Reconstruct realistic face models
- High-level controls to alter appearance

Photograph Rendered

Photograph Rendered

Target Skin Altered Appearance
Capturing Face Appearance

- **Explicit Modeling**
  - Geometry + texture
    - [Pighin et al. 1998]

- **Image-based Methods**
  - Reflectance fields
    - [Derevsek et al. 2006]
    - [Hawkins et al. 2004]

Skin Reflectance Models

- **BRDF** (bi-directional reflectance distribution function)
  - BRDF approximation of scattering
    - [Hanrahan and Krueger 1993]
    - [Stam 2001]
  - Image-based BRDF
    - [Marschner et al. 1999]

- **BSSRDF** (bi-directional surface scattering reflectance distribution function)
  - Single-layered skin model
    - [Jensen et al. 2001]
  - Multi-layered skin model
    - [Donner and Jensen 2005/2006]

- **BTF** (bi-directional texture function)
  - Spatially varying reflectance of skin patches
    - [Cula and Dana 2002]

Appearance Editing

- **Image-based editing**
  - Manual editing by skilled artists
  - Melanin/hemoglobin model
    - [Tsumura et al. 2003]

- **Morphable face model**
  - [Blanz and Vetter 1999]
  - [Fuchs et al. 2005]

Production Environment

- **Gemini Man**
  - [Williams et al. 2005]

- **Hulk, Harry Potter II**
  - [Her 2003/2005]

- **Matrix**
  - [Borshukov 2003]

- **Spider Man II**
  - [Sagar et al. 2004]

Project Contributions

- Acquisition hardware for the facial BSSRDF
  - Translucency measurements
  - Facial reflectance fields

- Practical skin model to be fitted
  - Simple, but realistic
  - Suited for production environments

- Analysis of physiological parameters
- Intuitive appearance editing framework

Outline

- Skin appearance acquisition
- Face data processing
- Reflectance Model Fit
- Reflectance Analysis
- Appearance Transfer
Skin Appearance

- Skin most important for facial appearance
- Main effects due to skin’s translucent layers

Epidermis

Dermis

Skin

Light transport affected by:
- Air/skin interface (reflectance/refraction)
- Epidermis, Dermis (scattering/absorption)

Reflectance Acquisition

M

fs

Rf

Translucency Measurements

Modulated BSSRDF

Surface BRDF

Reflectance Field + Geometry

“BSSRDF Gun”

- Subcutaneous light transport measurements
- Measures translucency (mean free path $\ell$)
  - Contact measurements
  - Light transport through optical fibers
- Suction pump ensures contact

“BSSRDF Gun”

Spherical acquisition dome
- 16 cameras @ 1300 x 1030
- 150 LED light sources
- Commercial 3D scanner

Reflectance Field Acquisition
Reflectance Field Acquisition

- Spherical acquisition dome
  - 16 cameras
    @ 1300 x 1030
  - 150 LED light sources
  - Commercial 3D scanner
- Dual-exposure HDR

Sample Reflectance Field

- 16 camera views
- 150 lighting directions
(images before radiometric correction)

Outline

- Skin appearance acquisition
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- Reflectance Analysis
- Appearance Transfer

Overview

Raw 3D Geometry  Geometry Cleaning  Cleaned Geometry

Overview

Raw 3D Geometry  Geometry Cleaning  Cleaned Geometry

Reflectance Images  Calibrations  Lumitexel Generation  Lumitexels
Camera Calibration

- **Intrinsics**
  - Using Intel OpenCV library
  - Based on checker-board images
- **Extrinsics**
  - \( n \)-camera calibration (\( n = 16 \))
  - Euclidian bundle optimization
  - Correspondences from LED swept through volume

Camera Calibration

- Vignetting & color calibration
  - Radial image intensity fall-off
  - Relative sensor calibration of all cameras
  - Affine color correction model \([\text{Funt} \ 2000]\)
  - Equalizes images taken under identical conditions
- Radiometric calibration
  - Implicitly through light source calibration
Light Source Calibration

- Desired parameters
  - Light source color
  - Light cone fall-off
- Fluorilon™ reflectance target
  - Perfect diffuse reflector
  - Reflects 99.9% of incident radiance
- Reflectance fields of different orientations
- Fitting 2nd-order polynomial to spot cross-section

“BSSRDF Gun” Calibration

- Relative fiber transmittance
  - Light table with opal glass diffuser
- Black image calibration
- Irradiance calibration
  - Skim milk as secondary standard
  - Values as measured by [JENSEN ET AL. 2001]

Overview

- Raw 3D Geometry
- Geometry Cleaning
- Geometry Refinement
  - Cleaned Geometry
  - Lumitexel Generation
  - Luminexels
  - Normal Estimation
  - Normal Map
- Model Fit

Geometry Refinement

- Geometry and normal information crucial
- Normal estimation
  - Photometric stereo
  - Lambertian assumption
  - Problem: bias, discontinuities
- Normal and geometry improvement adapting [NEHAB ET AL. 2005]
Outline

- Skin appearance acquisition
- Face data processing
- Reflectance Model Fit
- Reflectance Analysis
- Appearance Transfer

Skin Reflectance Model

- Skin Reflectance
- Diffuse Subsurface Scattering (BSSRDF)
- Specular Reflection (BRDF)

Skin Reflectance Model

Dipole Approximation
- Analytic model
- Isotropic scattering in homogeneous materials
- Modulation texture M

Torrance-Sparrow BRDF
- Physically based
- Micro-facets

Model Fit

Skin Reflectance

Photograph Reconstruction

Face Reconstruction

Photograph

Reconstruction

Reconstruction
Reconstruction

Photograph

Reconstruction

Face Reconstruction

Outline

- Skin appearance acquisition
- Face data processing
- Reflectance Model Fit
- Reflectance Analysis
- Appearance Transfer

Face Reconstruction

The Face Database

- Scanned 149 subjects
- Classification by
  - Skin type, gender, age, ...
  - Facial region
- Analysis of variation in model parameters

Translucency Variance

- Model validation
  - Facial scattering is isotropic

Cheek  Forehead  Abdomen
Translucency Variance

- Model validation
  - Facial scattering is isotropic
- Spatial translucency variance minute

Spatial BRDF Variance

Skin Trait Variations

- Canonical Correlation Analysis (CCA)
  - Directions of maximal correlation in BRDF parameter space
- BRDF: correlates with skin type and gender
- Albedo: highly correlated with skin type

Outline

- Skin appearance acquisition
- Face data processing
- Reflectance Model Fit
- Reflectance Analysis
- Appearance Transfer

Appearance Editing

- From parameter observations derive intuitive user controls
  - Main tool: texture synthesis
    [HEEGER AND BERGEN 1995],
    [MATUSIK ET AL. 2005]
  - Applicable to all model parameter types
  - Add freckles, moles, gloss variations, ...
- General appearance editing framework
Results Appearance Transfer

Target face
Freckles applied

Target face
Changed skin type

Target face
Lotion applied, Stubbles reduced

Contributions

- Acquisition hardware for the facial BSSRDF
  - Translucency measurements
  - Facial reflectance fields
- Practical skin model to be fitted
  - Simple, but realistic
  - Suited for production environments
- Analysis of physiological parameters
- Intuitive data-driven appearance editing framework
- Published appearance database of human faces

Potential Extensions

- Facial hair
  - Eye-brows, eye-lashes
  - Beard, stubbles
  - Velvety hair
- Spectral measurements
- Multi-layered model using additional model assumptions (e.g. [DONNER AND JENSEN 2006])
- Will increasing measurement accuracy increase the perceived degree of realism?

Q & A

Appearance database online at:
http://www.merl.com/facescanning/