IMPA Minicourse – Summer 2005
Photometric Calibration of Digital Cameras for Image-Based Techniques

Image-Based BRDF Measurement

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Course Structure

- digital image acquisition
- digital image formation
  - February 14th
- photometric calibration
  - relation between pixel values (digital counts) and physics
  - February 16th
- high dynamic range imaging
  - February 18th
- high dynamic range video
  - February 21st
- color calibration
  - February 23rd
- image-based BRDF measurement
  - February 25th

Appearance of a Surface

diffuse
mirror / specular
glossy / specular

Qualitative Description

diffuse
mirror / specular
glossy / specular

Forward/Backward Scattering

Anisotropic Reflections

- Highlights caused by anisotropic materials change when the surface is rotated around the surface normal
Pigmented Particles

- Many materials are composed by a substrate into which particles are embedded.
- White highlights are caused by reflection at the substrate’s surface
- Penetrating light is scattered and colored by pigments
- Subsurface scattering is typically ignored (surface reflection only)

Subsurface Scattering

- Light is shining through translucent alabaster

Translucent Materials

- Incident light may leave the object at a distant position after it is scattered beneath the surface

Volumetric Structures

- Highly complex geometry requires volumetric representations

Appearance Representation Taxonomy

- General Function - 12D
- Spatial time dependence (no phosphorescence)
- Assume independent wavelengths (no fluorescence)
- Discretized wavelength (RGB)

- Ignore time dependency (no phosphorescence)
- Assume independent wavelengths (no fluorescence)
- Discretized wavelength (RGB)

- Ignore subsurface scattering
- Assume planar homogeneous material
- Assume homogeneous material
- Ignore subsurface scattering

- Spatially Varying BRDF - 6D
- Bidirectional Subsurface Scattering Distribution Function (homogeneous BRDF) - 6D
- Spatially scattering function

- Bidirectional Reflectance Distribution Function (homogeneous BRDF) - 6D
- Isotropic single scattering function

- Spatially Varying BRDF - 8D
- Bidirectional Reflectance Distribution Function (heterogeneous BRDF) - 6D
- Isotropic single scattering function

- General Function - 12D
- Spatially Varying BRDF - 9D
- Assumption isotropy

- Bidirectional Reflectance Distribution Function (homogeneous BRDF) - 6D
- Isotropic single scattering function

- General Function - 12D
- Spatially Varying BRDF - 10D
- Assumption isotropy

- Bidirectional Reflectance Distribution Function (heterogeneous BRDF) - 6D
- Isotropic single scattering function

Digitizing Real World Objects

- by images
- no interaction
Digitizing Real World Objects

- by 3D geometry
  - no color

- by geometry plus texture
  - no relighting

- by geometry plus a single BRDF

- by geometry plus reflection properties

Appearance Acquisition

- Question: How will the object look like in different environments and/or for different views?
  - Requires to represent the interaction of light with the object:
    - data base representation using interpolation
    - representation by parameterized functions

Lightfield (4D)

- [Levoy 1996, Gortler 1996]
  - store only excitant rays (fixed environment)
  - can be acquired by moving the camera around the object
  - reconstruction by view-interpolation
Simplified Reflectance Field

- assume directional or point light sources (6D)
- keep viewing position fixed (4D)
- acquired using the light stage
  - large amount of technical equipment
  - huge amount of data but low angular resolution
  - successfully applied to faces

Reflection Properties

- BRDF (bi-directional reflectance distribution function)
  
  \[
  f(\hat{\omega}_o, \hat{\omega}_i)
  \]
  
  yields the fraction of reflected to incident radiance at one point for any pair of directions.

BRDF Measurement

- Gonioreflectometer
  - produces huge table of measurement data for pairs of directions
  - dense sampling required to model narrow highlights faithfully
  - works only for
    - homogeneous materials
    - flat material samples

Bidirectional Texture Functions (BTFs)

- [Dana et al., 1999]
- Reflectance field of a planar texture
- Replicated over a synthetic surface
- Captures shadowing and masking effects due to macro structure.
  - Tabulated Spatially Varying BRDF
  - No geometry at silhouettes
Photometric Calibration of Digital Cameras for Image-Based Techniques

BTF Acquisition

- Material sample

Principle Component Analysis (PCA)

- Problem with Reflectance Fields:
  - Huge amount of data
  - Often compression is applied, e.g. PCA:
  - Write the measurements of each pixel as vector
  
  \[
  \vec{r}_{xy} = \left( \begin{array}{c}
  R_{xy}(\theta_1, \phi_1) \\
  R_{xy}(\theta_2, \phi_2) \\
  \vdots \\
  R_{xy}(\theta_n, \phi_n)
  \end{array} \right)
  \]

PCA

- Compute Covariance matrix
  \[
  \mathbf{C} = \mathbf{R}^T \mathbf{R} \quad \text{with} \quad \mathbf{R} = \frac{1}{m} \sum_{j=1}^{m} \vec{r}_{jz} \vec{r}_{jz}^T
  \]
  - Compute Eigenvalues \( \lambda_1, \ldots, \lambda_m \) and vectors \( \vec{e}_1, \ldots, \vec{e}_m \) forming an orthonormal basis
  - Each vector can be written as
  
  \[
  \vec{r}_{ij} = \vec{F} + \sum_{i=1}^{k} c_i \vec{e}_i
  \]

PCA-Compression

- Sort eigenvalues (exponential fall-off).
- Use only the most important \( k \) components (ksm)
- Equivalent to projecting the \( m \)-dimensional vector space into a \( k \)-dimensional vector space, i.e. compressing the vector space in the directions of lowest variance

BRDF Measurement

- Gonioreflectometer
Image-Based BRDF Measurement

- Marschner 1999
- capture lots of BRDF samples at one shot by a sensor array / camera
- store the acquired samples in a large table
- interpolate nearby values for reconstruction

Digitizing Real World Objects

- by geometry plus a single BRDF

Goal

- measure reflection properties per texel

Overall Goal

- measure the reflection properties of each texel using a small number of images
- problems:
  - too few radiance samples per texel
  - no dense sampling of the BRDF
  - no reconstruction possible
- approach:
  - measure the reflection properties of the basic materials
  - describe the reflection properties of each texel as a weighted sum of the basis BRDFs

Acquisition Equipment

- 3D scanner
- digital camera
- point-light source
- dark room
- calibration targets (checkerboard, metal spheres)

Acquisition Equipment

- software
  - central MPI software repository
    - base, IBR, GMU, ...
  - cross-platform via tmk
    - see http://sourceforge.net/projects/tmk
  - standard tools for many purposes
    - HDR imaging and recovery
    - mesh processing
    - ...

Photometric Calibration of Digital Cameras for Image-Based Techniques

Acquisition

- HDR images, calibrated camera/light source position
- 3D scan

3D-2D Registration

- calibrated gantry
- corresponding points
- silhouette-based method

Light Source Position

- detect highlights of ring flash reflections
- determine the position of the spheres

- detect highlights of light source reflections
- reconstruct light source position

Light Source Position

- A lumitexel $L$ collects all data available for a point on the surface:
  - 3D position $\mathbf{x}$
  - normal $\mathbf{n}$
  - list of radiance samples $R_{\mathbf{x}}$ for every image where $\mathbf{x}$ is visible and lit:
    - radiance value $r_i$
    - light source direction $\mathbf{v}_i$
    - viewing direction $\mathbf{u}_i$

Lumitexels

- from geometry
- from images
Assembling Lumitexels

- for each point on the surface:
  - find all images where the point is visible and lit
  - take sample at corresponding pixel position

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The Lafortune Model

\[ f_r(\hat{u}, \hat{v}) = \rho_d + \sum_i C_i(u, v, \nu, \hat{u}, \hat{v}, \lambda) \]

- physically plausible
- diffuse component plus a number of lobes
- \(3(1+1^3)\) parameters (12 for a single lobe model)
- fit parameters to samples

Fitting BRDFs to Lumitexels

- define error measure between a BRDF and a lumitexel:

\[ E_f(L) = \frac{1}{|L|} \sum_{r \in L} \Delta f_r(\hat{u}, \hat{v}) u_{r_r}, v_r \]

- perform non-linear least square optimization for a set of lumitexels using Levenberg-Marquardt
- yields a single BRDF (i.e. its parameters) per set of lumitexels

Fitting Result
Clustering

- Goal: separate the different materials
  - similar to Lloyd iteration
  - start with a single cluster containing all lumitexels
  - split cluster along direction of largest variance
  - stop after n clusters have been constructed

Split-Recluster-Fit Cycle

- split into two BRDFs
- distribute initial texels forming two new clusters
- refit new BRDFs
- repeat reclustering and fitting until clusters are stable

Clustering Results

Spatially Varying Materials

Spatially Varying BRDFs

- goal: assign a separate BRDF to each lumitexel
- problem: too few radiance samples for a reliable fit of the parameters

Overall Goal

- measure the reflection properties of each texel using a small number of images
- problems:
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  - no reconstruction possible
- approach:
  - measure the reflection properties of the basic materials
  - describe the reflection properties of each texel as a weighted sum of the basis BRDFs
too few radiance samples for a reliable fit
represent the BRDF $f_\lambda$ of every lumitexel by a weighted sum of already determined BRDFs of the clusters $f_1, f_2, \ldots, f_m$:
$$ f_\lambda = t_1 f_1 + t_2 f_2 + \ldots + t_m f_m $$
determine linear weights $t_1, t_2, \ldots, t_m$

compute the pseudo-inverse using SVD to get a least squares solution for

$$ \begin{bmatrix} f_1&f_2&\ldots&f_m \end{bmatrix} \begin{bmatrix} t_1 \\ t_2 \\ \vdots \\ t_m \end{bmatrix} = \begin{bmatrix} r_1 \\ r_2 \\ \vdots \\ r_k \end{bmatrix} $$

avoid negative $t_j$

Reconstruction Results
Normals and Reflection

- for fixed (global) lighting and viewing direction reflectance changes with normal direction

\[
\omega_0 \cdot n_i = \omega_0 \cdot \hat{n}
\]

Measuring Normal Maps

- [Rushmeier '97]
- shape from shading / photometric stereo
- assume diffuse surfaces: \( f(\hat{\omega}_i, \hat{\omega}_s, \hat{\omega}_r) = \rho \)
- outgoing radiance:
  \[
  L_o = \rho L_i \cdot (\hat{\omega}_i \cdot \hat{n})
  \]
- take three pictures with different light source positions

\[
\rho L_i \cdot \omega_{0,1} \cdot \omega_{1,1} \cdot n_i = \begin{bmatrix} L_{0,3} \\ L_{1,2} \\ L_{2,1} \end{bmatrix}
\]

Normal Maps for arbitrary BRDFs

- complex BRDFs require optimization
- start with \( f = t_1 f_1 + t_2 f_2 + \ldots + t_m f_m \)
  using the previously determined \( t_1, t_2, \ldots, t_m \)
  and the normal provided by the initial mesh;
- optimize for the normal direction and \( t_1, t_2, \ldots, t_m \)
  at the same time using Levenberg-Marquardt.
Normal Maps Results

Without Normal Fitting

With Normal Fitting

Planned Sampling

Sampling Goals

Multi-Pixel Objects

Sampling Goals

- Sample the surface evenly.
- Sample the reflection properties for each surface point from the most interesting directions.
- Increase the certainty in the estimated reflection parameters.
- Avoid complicated bookkeeping!

Multi-Pixel Objects

- View planning by uncertainty minimization.
- A Hessian matrix needs to be evaluated for each point on the surface.
- Real-World Constraints:
  - Visibility
  - Shadows
  - Restrictions on camera and light source placement
    - Camera and light source have to be a minimum distance apart (set objective function to zero).
    - Sampling at grazing angles is undesirable since it amplifies geometric errors (weight by the cosine).
Case Study - Minerva

- Greek bronze statue of Minerva, under restoration (Florence, Italy)
- Extensive cleaning (large corrosion deposits)
- Some “fake” parts that were added in previous restorations will be removed
- Various stages of the restoration documented by digital 3D models:
  - 4 complete scanning (2000-2002)
  - acquisition of reflectance properties

Case Study

acquisition of the reflection properties of the head in an intermediate state (February 2003)

- first acquisition outside lab environment
- large room helped to reduce interference
- good acquisition quality achieved

Results – Minerva Head

- live demo
Results – Minerva Head
- correct reproduction of original object
- reproduces the original "look and feel"

Accuracy of the Acquired Model
- compare renderings with photographs captured under identical conditions
- quality metric: ΔE

Accuracy of Renderings
- visual comparison between rendering (on screen, printout) and real object under identical conditions

Conclusion
- Further step towards capturing all the richness and complexity of real objects
- "More than Color" — required for various materials
- Acquisition on-site possible as demonstrated for the Minerva
- Accurate capture of the current state of an object as part of a 3D scanning effort
- Detailed models enabling interactive viewing on current standard PC hardware

Wrap-Up
- overview of surface properties
- taxonomy of surface representations
- image-based BRDF measurements
  - normal fitting
  - acquisition planning
- case study

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The End!