Welcome to Computer Graphics III

Capturing Reality
Prof. Dr.-Ing. Michael Goesele
Graphisch Interaktive Systeme (GRiS)
TU Darmstadt

Preliminaries
- Computer Graphics III (Graphische Datenverarbeitung III)
- This instance: Capturing Reality – Digitalisierungstechniken in der Graphischen Datenverarbeitung
- Instructor: Prof. Dr.-Ing. Michael Goesele
  michael.goesele@gris.informatik.tu-darmstadt.de
  Room 311, IGD Building

Preliminaries
- Time: Monday 14:25 – 16:05
- Exercises: Tuesday 12:35 – 14:15
- Location: Room 074 IGD Building
  Exceptions: 22.10. and 05.11. in Room 073
- Prerequisites: Computer Graphics I and II

Course Content
- basic tools and calibration techniques
- selection of state-of-the-art capturing techniques
- basic set of relevant mathematical modeling and optimization techniques

Digitizing Real World Objects
- by images
- no interaction
Digitizing Real World Objects

- by 3D geometry
- no color

Digitizing Real World Objects

- by geometry plus texture
- no relighting

Digitizing Real World Objects

- by geometry plus a single BRDF

Digitizing Real World Objects

- by geometry plus reflection properties

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

[Diagram of Gonioreflectometer with light source, sensor, and sample]
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 and flat material samples

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
- HDR images, calibrated camera/light source position

Acquired Data
- 18 input images (HDR)
- sparse sampling of spatially varying BRDF

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

![Diagram of light source position](image)

### Light Source Position

- Detect highlights of light source reflections
- Reconstruct light source position

![Diagram of light source position](image)

### Lumitexels

- A lumitexel $L$ collects all data available for a point on the surface:
  - 3D position $\vec{x}$
  - Normal $\vec{n}$
  - List of radiance samples $R_{ij}$ for every image where $\vec{x}$ is visible and lit:
    - Radiance value $r_i$
    - Light source direction $\vec{l}_i$
    - Viewing direction $\vec{v}_i$

  \[ \{ \text{from geometry} \} \quad \{ \text{from images} \} \]

![Diagram of lumitexels](image)

### Assembling Lumitexels

- For each point on the surface:
  - Find all images where the point is visible and lit
  - Take sample at corresponding pixel position

![Diagram of assembling lumitexels](image)

### Overall Goal

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  - Approach:
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    - Describe the reflection properties of each texel as a weighted sum of the basis BRDFs

![Diagram of overall goal](image)
The Lafortune Model

\[ f_r(\hat{\vec{u}}, \hat{\vec{v}}) = P_d + \sum_i (C_i u_i v_i) + (C_i' u_i' v_i') \]

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

Fitting BRDFs to Lumitexels

- define error measure between a BRDF and a lumitexel:
  \[ E_K(L) = \frac{1}{|U|} \sum_{\vec{r} \in L} \Delta(f_r(\hat{\vec{u}}, \hat{\vec{v}})u_{i,z} r_i)^2 \]
- 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

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Projection

- too few radiance samples for a reliable fit
- represent the BRDF \( f_x \) of every lumitexel by a weighted sum of already determined BRDFs of the clusters \( f_1, f_2, \ldots, f_m \):
  \[
  f_x = t_1 f_1 + t_2 f_2 + \ldots + t_m f_m
  \]
- determine linear weights \( t_1, t_2, \ldots, t_m \)

Reconstruction Results

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

\[
\begin{bmatrix}
  f_1(u_1, v_1)u_{t_1} & f_1(u_2, v_2)u_{t_2} & \cdots & f_m(u_1, v_1)u_{t_m} \\
  f_1(u_2, v_2)u_{t_1} & f_1(u_2, v_2)u_{t_2} & \cdots & f_m(u_2, v_2)u_{t_m} \\
  \vdots & \vdots & \ddots & \vdots \\
  f_1(u_m, v_m)u_{t_1} & f_1(u_m, v_m)u_{t_2} & \cdots & f_m(u_m, v_m)u_{t_m}
\end{bmatrix}
\begin{bmatrix}
  t_1 \\
  t_2 \\
  \vdots \\
  t_m
\end{bmatrix} = \begin{bmatrix}
  f_1(u_1, v_1) \\
  f_1(u_2, v_2) \\
  \vdots \\
  f_1(u_m, v_m)
\end{bmatrix}
\]

- avoid negative \( t_j \)
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Normals and Reflection

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

Real Geometry

Normal Map

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Measuring Normal Maps

[Rushmeier '97]

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

\[
\rho L_i \begin{pmatrix}
\omega_{1,1} & \omega_{1,2} & \omega_{1,3} \\
\omega_{2,1} & \omega_{2,2} & \omega_{2,3} \\
\omega_{3,1} & \omega_{3,2} & \omega_{3,3}
\end{pmatrix}
\begin{pmatrix}
n_1 \\
n_2 \\
n_3
\end{pmatrix}
=
\begin{pmatrix}
L_{n,1} \\
L_{n,2} \\
L_{n,3}
\end{pmatrix}
\]

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

- Where to place the camera and the light source in order to perform an efficient/more precise acquisition?

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!

Applied to Real 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).

Applied to Real Objects

- Plot of uncertainty during an acquisition
  - Top row: planned approach
  - Bottom row: human expert
  - Uncertainty decreasing black → red → blue

Summary

- Complete (large) acquisition pipeline for spatially varying BRDFs of objects
- Appearance model suitable for realistic rendering
- Pointers to important aspects
  - Will be covered in future lectures
Outlook

- next 2 lectures:
  - cameras
  - geometric calibration
  - photometric calibration
  - high-dynamic range imaging
  - homework assignment related to calibration
- more on capturing reality …
- Looking for tutor for GDV II!