Capturing and Rendering the World of Materials

Wenzel Jakob
Joint work with Jonathan Dupuy
A new database of surface appearance
# A new database of surface appearance

1. **Why?**

2. **Prior work**

3. **Hardware**

4. **Microfacet theory**

5. **Our method**

6. **Demo**
Standard materials in rendering systems
Standard materials in rendering systems
Why does it matter?
Why does it matter?

- Scientific method
Why does it matter?

• Scientific method
Why does it matter?

- Scientific method
- Entertainment
Why does it matter?
Why does it matter?
The BRDF

\[ f_r = f_r(\omega_i, \omega_o, \lambda) \]
The BRDF

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The BRDF

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Isotropic BRDFs

• If the BRDF is unchanged as the material is rotated around the normal, then it is \textit{isotropic}, otherwise it is \textit{anisotropic}.
Isotropic BRDFs

• If the BRDF is unchanged as the material is rotated around the normal, then it is *isotropic*, otherwise it is *anisotropic*.

• Isotropic BRDFs are functions of just 4 variables (instead of 5)
Why is measuring BRDFs hard?

1 measurement / second

100^2

100^2
Why is measuring BRDFs hard?

1 measurement / second

$100^2$

$100^2$
Why is measuring BRDFs hard?

Curse of dimensionality: **3 years** of measurement time
“Evading” the curse of dimensionality

A New Change of Variables for Efficient BRDF Representation

[Rusinkiewicz 98]
“Evading” the curse of dimensionality

A New Change of Variables for Efficient BRDF Representation

[Rusinkiewicz 98]
Prior work
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- **MERL database** [Matusik et al. 2003]
  - First comprehensive repository of reflectance data.
  - Landmark paper & dataset – used in hundreds of papers.
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  - First comprehensive repository of reflectance data.
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... but MERL is not without problems.
Issues with the MERL approach
Issues with the MERL approach

1. Acquiring multiple directions at once using a camera
Issues with the MERL approach

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2. Restriction to spherical samples
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3. Restriction to isotropy
Issues with the MERL approach

1. Acquiring multiple directions at once using a camera

2. Restriction to spherical samples

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4. Interpretation of data
Issues with the MERL approach, contd.
5. Fixed sampling pattern: dense discretization necessary.
Issues with the MERL approach, contd.

5. Fixed sampling pattern: dense discretization necessary.

6. No importance sampling
Issues with the MERL approach, contd.

5. Fixed sampling pattern: dense discretization necessary.

6. No importance sampling

7. Extrapolation artifacts, oscillatory behavior
EPFL’s gonio-photometer

[PAB Ltd.]
EPFL’s gonio-photometer
Sensors

Modular head:

1. Silicon photodiodes
2. Spectrometer (320-1200nm)
Sensors, contd.

Modular head:

3. 26 MPix CCD (RGB/Bayer)
4. 24 MPix CMOS (mono)
Problem with this approach:
- fast along 1 dimension
- .. but what about remaining 3?

Curse of dimensionality remains
High level idea

1. Measurement locations should be chosen adaptively
High level idea

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High level idea

1. Measurement locations should be chosen adaptively

2. Importance sampling seems useful?
The central conundrum

- Importance sampling would be ideal:
  - Samples correspond to “interesting” locations, where the BRDF takes on non-negligible values.

- But: to importance sample the material, we must already have measured it.
The central conundrum

• Importance sampling would be ideal:
  - Samples correspond to “interesting” locations, where the BRDF takes on non-negligible values.

• But: to importance sample the material, we must already have measured it.

Is there something else that is
1. quick to measure, and
2. informative?
Retro-reflection to the rescue

\[ R(\omega) = f_r(\omega, \omega, 532 \text{ nm}) \]

Diffuse  Specular & isotropic  Anisotropic
Review: microfacet theory

Smooth conducting material

Smooth dielectric material
Review: microfacet theory

Smooth conducting material

Smooth dielectric material

Rough conducting material

Rough dielectric material
Microfacet theory

- Model interactions with a random surface microstructure
Microfacet theory

- Model interactions with a random surface microstructure
Microfacet theory

• Model interactions with a random surface microstructure
Microfacet theory

- Model interactions with a random surface microstructure
Microfacet theory

- Model interactions with a random surface microstructure
Microfacet theory

• Model interactions with a random surface microstructure
A helpful connection
A helpful connection
A helpful connection

intuition: \( f_r^\perp (\omega_i = \omega_o) \propto D(\omega_h) \)
Putting things together..
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1. Measure retroreflection (2D only, i.e. fast)
Putting things together..

1. Measure retroreflection (2D only, i.e. fast)
2. Convert to microfacet distribution
Putting things together..

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3. Importance sample microfacet model
Putting things together..

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4. Measure
Putting things together..

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5. Profit!
Putting things together..

1. Measure retroreflection (2D only, i.e. fast)
2. Convert to microfacet distribution
3. Importance sample microfacet model
4. Measure
5. Profit!

Not so fast:
1. Will we be restricted to materials that match microfacet theory?
2. how to evaluate the model?
Importance sampling

Goal: generate random samples $x$ proportional to $f(x)$
Importance sampling

**Goal:** generate random samples $x$ proportional to $f(x)$
Inverse transform sampling

• The inversion method:
Inverse transform sampling

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  1. Compute the CDF \( P(x) = \int_0^x p(x') \, dx' \)
Inverse transform sampling

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  3. Obtain a uniformly distributed random number $\xi$
  4. Compute $X_i = P^{-1}(\xi)$
Importance sampling as a parameterization
The final pipeline

**ACQUIRE**

- Regular grid

**WARP 1**

- VNDF (4D)
- $u_1, u_2$
- $(\theta_i, \phi_i)$

**WARP 2**

- $g_2$

**WARP 3**

- $g_3$
- $\omega_h$
The final pipeline

\[ g_3 \]

\( \omega_i \)

\( \omega_o \)

\text{WARP 3}

\text{CAPTURE}

\text{WEIGHT}
The final pipeline

\[ g_3 \]

\( \omega_i \)
\( \omega_o \)

Capture

Weight

Inverse Warp 1

Inverse Warp 2

Evaluate

\( g_3^{-1} \)

\( g_2^{-1} \)

(\( u_1, u_2 \))
The final pipeline

\( g_3 \)

\( \omega_i \)

\( \omega_o \)

\( \text{Warp 3} \)

\( \text{Capture} \)

\( \text{Weight} \)

\( \text{Inverse Warp 3} \)

\( g_1^{-1} \)

\( \text{Interpolate} \)

\( \text{Spectra (5D)} \)

\( (u_1, u_2) \)

\((s_1, s_2)\)

\( (\theta_i, \phi_i, \lambda) \)

360nm

1000nm
Optical setup: spectral acquisition

- Xenon arc lamp
- Collimation lens
- Focusing lens
- Pinhole
- Sensor
- Sample
Optical setup: retro-reflection
Measurement setup

- DPSS laser
- Kinematic mirrors (2x)
- Electronic shutter
- Beam expander
- Beamsplitter
- Beam dump
- Collimation lens
- Faraday isolator
- Photodiode
- Pinhole
- Electronic shutter
- Xenon arc light source
- Focusing lens
Measurement setup
Step 1: retro-reflective acquisition (x8)
Step 1: retro-reflective acquisition (x8)
6 aurora-white
Description: TeckWrap vinyl wrapping film ("Aurora White DCH02")
Renderings

19 ibiza-sunset
Description: Car wrap material (Teckwrap Ibiza Sunset RD02)
Renderings

20 iridescent-flake-paint2
Description: Iridescent car paint with flakes
Renderings
**36 ibiza-sunset**

Description: Car wrap material (Teckwrap Ibiza Sunset RD02)

**Plots**

**Slices**

**Sample Locations**

**Renderings**

**29 northern-aurora**

Description: Car wrap material (Teckwrap Northern Aurora RD05)

**Plots**

**Slices**

**Sample Locations**

**Renderings**

**31 silk-blue**

Description: Blue car wrap (Teckwrap Silk Blue VCH502N)

**Plots**

**Slices**

**Sample Locations**

**Renderings**

**20 iridescent-flake-paint2**

Description: Iridescent car paint with flakes

**Renderings**

**Plots**

**Slices**

**Sample Locations**
Material database: microfacet-like

vch_dragon_eye_red    vch_frozen_amethyst    vch_silk_blue    vch_ultra_pink
Material database: microfacet-like

- aniso_copper_sheet
- aniso_metallic_paper_copper
- aniso_metallic_paper_gold
- aniso_brushed_aluminium_1
Material database: microfacet-like (??)

satin_blue  satin_gold  satin_purple  satin_white
Material database: microfacet-like (??)

aurora_white  cc_nothern_aurora  cc_ibiza_sunset  cc_amber_citrine
Iridescent butterfly

aniso_morpho_melenaus
Iridescent butterfly

aniso_morpho_melenaus
Anisotropic fabrics

aniso_sari_silk_2color
Anisotropic fabrics

aniso_sari_silk_2color
Broad wavelength coverage

(a) D65

(b) Fluorescent

(c) Incandescent

(d) Infrared
Post-processing

Slices (raw)

Slices (post-processed)

Shadowed!
Resources

Hardware

Spectral 4-Axis Gonio-Photometer

Data

Material Database

Software

Tekari

Benoit Ruiz, Tizian Zeltner, and Wenzel Jakob
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Hardware

Spectral 4-Axis Gonio-Photometer

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Tekari

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<table>
<thead>
<tr>
<th>Material</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>acrylic_felt_white</td>
<td>White acrylic felt (Edukit A4)</td>
</tr>
<tr>
<td>acrylic_felt_yellow</td>
<td>Yellow acrylic felt (Edukit A4)</td>
</tr>
<tr>
<td>aniso_brushed_aluminium</td>
<td>Brushed aluminium sheet (<a href="https://www.gah.de/profile-bleche/produkte/reparatur-und-bastlerbleche-1/glattblech-8/">https://www.gah.de/profile-bleche/produkte/reparatur-und-bastlerbleche-1/glattblech-8/</a>)</td>
</tr>
<tr>
<td>aniso_copper_sheet</td>
<td>Smooth copper sheet -- anisotropic</td>
</tr>
<tr>
<td>aniso_metallic_paper_copper</td>
<td>Copper metallic foil card</td>
</tr>
<tr>
<td>aniso_metallic_paper_gold</td>
<td>Gold metallic foil card</td>
</tr>
<tr>
<td>aniso_miro_7</td>
<td>Alanod Miro #7 5000GP aluminium sample</td>
</tr>
<tr>
<td>aniso_morpho_melenaeus</td>
<td>Morpho melanaus specimen (male, scan covers dorsal surface of right fore wing)</td>
</tr>
</tbody>
</table>
The importance of good parameterizations

\[ \theta_i \]

NDF

VNDF
The importance of good parameterizations

\[ \theta_i \]

(a) NDF

(b) VNDF

Hierarchical sample warping

Marginal-conditional (naïve)

Marginal-conditional (exact)

Marginal-conditional (+weighting)
Contributions
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• A unified algorithm for BRDF acquisition, representation, and rendering
  - Low storage requirements (16 KiB per channel)
  - Significantly fewer samples (3712 measurements vs >100K for MERL).
  - Built-in importance sampling.
  - Handles anisotropy
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• A hardware modification for scanning gonio-photometers.

• A database of spectral BRDFs (isotropic & anisotropic, currently 57 materials).
Questions?

http://rgl.epfl.ch/materials