Optical measurement techniques for complex fenestration systems (CFS)

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Outline

- Optical properties
- Spectrophotometers
- Definition of BRDF, BTDF, BSDF
- Goniophotometer measurements
- Imaging system measurements
- Other methods
- Data representation
- Questions
Examples of CFS
Direct-hemispherical properties

- Reflectance and transmittance
  - Wavelength
  - Angle of incidence
  - Polarization
  - Temperature, tension, magnetic field
- Direct-direct, specular
- Direct-diffuse, scattered-only
- Direct-hemispherical, total = $ds + dd$
Wavelengths of light

- Optical properties are $\lambda$ dependent
- Light sources have different intensity at different $\lambda$
- Detectors have different sensitivity at different $\lambda$
Measuring transmittance and reflectance

• Relative measurement between reference case of no sample and sample

\[ T = \frac{\text{Sample}}{\text{Reference}} \]

(world's easiest job)
Spectrophotometer

- Scanning spectrophotometer
- Optical multichannel analyzer is different
Definition of total, diffuse, specular

- $T_{diff}$ and $R_{diff}$ are obtained by opening a port and letting the specular component out.
- $T_{spec}$ is calculated as $T_{total} - T_{diff}$ hence, $T_{spec}$ is instrument defined.
Variable angle of incidence

- Still direct-hemispherical
- Characterization of fabrics with angle tubes
- Outdoor sphere
- Center mount for opaque samples
Examples of data
Where does light go

• Many applications require knowledge how much light goes in different directions

• Ratio is no longer useful since there is an infinite amount of outgoing directions

- Oh, no, no. I was just wondering if you could help me find my way.
- Well that depends on where you want to get to.
- Oh, it really doesn't matter, as long as...
- Then it really doesn't matter which way you go.
BRDF – The Bi-directional Reflectance Distribution Function

• Fred E. Nikodemus wrote “Directional Reflectance and Emissivity of an Opaque Surface” in 1965

\[ \text{BRDF}(\theta_i, \theta_p) = \frac{P_r/\Omega_p}{P_i \cos\theta_p} \]

• Not his definition but more useful for experiments
BTDF – Same thing for transmittance

- Transparent samples both BRDF and BTDF
- The combination is often denoted as BSDF (Scattering) or B(R/T)DF
- Definition of angle coordinates needed
Properties of the BSDF

- Main parameters are incident and outgoing angles – continuous definition space
- Wave properties – wavelength (band), polarization state
- Sample properties – temperature, dirt
Famous BRDF values

- **$1/\pi$** – A surface of constant BRDF of $1/\pi$ for all outgoing angles will have a direct-hemispherical reflectance of 1. Constant BSDF values are called Lambertian.

- **2** – BRDF-values can be larger than one without violating energy conservation.

- **-1** – BRDF-values lower than 0 are not physical.
Goniophotometer approach

- We put a small detector covering a space angle $\Omega$ at a given outgoing angle we detect $P_r$. By knowing $P_i$ we can directly calculate the BRDF.
Examples of data
Pros and cons of goniophotometer

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
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</thead>
<tbody>
<tr>
<td>• Intuitive</td>
<td>• Slow</td>
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<tr>
<td>• High, variable, angle-resolution</td>
<td>• Retroreflection is hard</td>
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<tr>
<td>• Modular with respect to sources and detectors</td>
<td>• $P_s$ often $&lt;&lt; P_i$</td>
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<tr>
<td>• Can handles some inhomogeneities in the sample</td>
<td>• Large instrument to obtain far field</td>
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Imaging approach

- Key is a semitransparent specular hemisphere or hemiellipsoid
- Sample in one focal point and a camera with a fisheye lens in the other
Imaging approach take 2

- Lambertian hemisphere
- Sample in one focal point and a curved mirror camera in the other
- Camera takes picture of the curved mirror
Pros and cons of imaging systems

Pros

• Very fast
• Measures same outgoing angles every time

Cons

• CCD cameras
  – Dynamic range
  – Calibration is hard
• Large instrument to obtain far field
• Depth of field at focal points
Other methods - pullback
Pros and cons of pullback method

Pros
• Cheap if you already have a spectrophotometer
• Spectral resolution

Cons
• Only near normal AoI
• Only isotropic
• Reflectance is hard
• Numerical solution is not good for BTDFs with large derivatives
Other methods

Bench-top spectrophotometers
In-situ detectors

Cons
- Extrapolation of data
- Inaccuracy
Data representation

- **Continuous function**
  - Probability density function
  - Cumulative distribution function
- **Discrete values**
  - Variable or fixed space
  - Association of space angle with measured values
Continuous Function – Data fitting

- Lambertian and Super-Lambertian
  - Convenient

- ABg-like
  - Scattering vector approach

- Any function that is representative of your sample
Discrete values – Klems basis

- Fixed space
- Clearly defined solid angle for each value
- Similar to Tregenza
Binning data into fixed coordinate system

• Voronoi diagram to associate an area with each point
• Match against target coordinate system
Summary

- Different ways to measure different properties that are relevant
- Direct-hemispherical versus BSDF
- Helpful to know end use
Questions?