Hyperspectral Image (HSI) Set to RGB Image

Computational Photography

CSE 273

Lecture 3
Announcements

• Assignment 1 is due today, 11:59 PM
• Assignment 2 will be released today
  – Due Jan 24, 11:59 PM
Burst photography

• Acquisition of several images by a single camera in quick succession
Burst photography

• Hyperspectral image (HSI) set

Color filter wheel

An image for each filter
Multispectral and hyperspectral images

• Multispectral (including RGB) images
  – In general, moderate spectral resolution (e.g., \(~100\) nm passband per channel)
  – 2 to 100 bands (channels)
  – In general, noncontiguous electromagnetic spectrum range

• Hyperspectral images
  – High spectral resolution (e.g., \(10\) nm passband per channel)
  – 100 to 1000 bands (channels)
  – Contiguous coverage of the spectrum range
Burst photography

- Hyperspectral image (HSI) set to RGB image
Electromagnetic spectrum

Increasing Frequency (ν) →

Increasing Wavelength (λ) →

Visible spectrum
Hyperspectral image (HSI) set to RGB image

• Motivation
  – What does the scene look like (to a human)?
  – Registration of a hyperspectral image set and an RGB image
Measuring color spectrum is a function of the spectrum of the illumination and reflectance.

From Foundations of Vision, Brian Wandell, 1995, via B. Freeman slides
Illumination spectra

• Different illumination spectra yield different measured color spectra

From Foundations of Vision, Brian Wandell, 1995, via B. Freeman slides
# Standard illuminants

Hue of each white point, calculated with luminance $Y = 0.54$

<table>
<thead>
<tr>
<th>Name</th>
<th>CIE 1931 2° $x_2$ $y_2$</th>
<th>CIE 1964 10° $x_{10}$ $y_{10}$</th>
<th>CCT (K)</th>
<th>Hue</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.44757 0.40745</td>
<td>0.45117 0.40594</td>
<td>2856</td>
<td>Orange</td>
<td>Incandescent / Tungsten</td>
</tr>
<tr>
<td>B</td>
<td>0.34842 0.35161</td>
<td>0.34900 0.35270</td>
<td>4874</td>
<td>Gray</td>
<td>[obsolete] Direct sunlight at noon</td>
</tr>
<tr>
<td>C</td>
<td>0.31006 0.31616</td>
<td>0.31039 0.31905</td>
<td>6774</td>
<td>Purple</td>
<td>[obsolete] Average / North sky Daylight</td>
</tr>
<tr>
<td>D50</td>
<td>0.34567 0.35850</td>
<td>0.34773 0.35952</td>
<td>5003</td>
<td>Blue</td>
<td>Horizon Light. ICC profile PCS</td>
</tr>
<tr>
<td>D55</td>
<td>0.33242 0.34743</td>
<td>0.33411 0.34377</td>
<td>5503</td>
<td>Blue</td>
<td>Mid-morning / Mid-afternoon Daylight</td>
</tr>
<tr>
<td>D65</td>
<td>0.31271 0.32902</td>
<td>0.31382 0.33100</td>
<td>6504</td>
<td>Blue</td>
<td>Noon Daylight: Television, sRGB color space</td>
</tr>
<tr>
<td>D75</td>
<td>0.29902 0.31485</td>
<td>0.29968 0.31740</td>
<td>7504</td>
<td>Blue</td>
<td>North sky Daylight</td>
</tr>
<tr>
<td>E</td>
<td>1/3 1/3 1/3 1/3</td>
<td>1/3 1/3 1/3 1/3</td>
<td>5454</td>
<td>Gray</td>
<td>Equal energy</td>
</tr>
<tr>
<td>F1</td>
<td>0.31310 0.33727</td>
<td>0.31811 0.33559</td>
<td>6430</td>
<td>Green</td>
<td>Daylight Fluorescent</td>
</tr>
<tr>
<td>F2</td>
<td>0.37208 0.37529</td>
<td>0.37925 0.36733</td>
<td>4230</td>
<td>Green</td>
<td>Cool White Fluorescent</td>
</tr>
<tr>
<td>F3</td>
<td>0.40910 0.39430</td>
<td>0.41761 0.38324</td>
<td>3450</td>
<td>Green</td>
<td>White Fluorescent</td>
</tr>
<tr>
<td>F4</td>
<td>0.44018 0.40329</td>
<td>0.44920 0.39074</td>
<td>2940</td>
<td>Green</td>
<td>Warm White Fluorescent</td>
</tr>
<tr>
<td>F5</td>
<td>0.31379 0.34531</td>
<td>0.31975 0.34246</td>
<td>6350</td>
<td>Green</td>
<td>Daylight Fluorescent</td>
</tr>
<tr>
<td>F6</td>
<td>0.37790 0.38635</td>
<td>0.36660 0.37947</td>
<td>4150</td>
<td>Green</td>
<td>Lite White Fluorescent</td>
</tr>
<tr>
<td>F7</td>
<td>0.31292 0.32933</td>
<td>0.31569 0.32960</td>
<td>6500</td>
<td>Green</td>
<td>D55 simulator, Daylight simulator</td>
</tr>
<tr>
<td>F8</td>
<td>0.34588 0.36875</td>
<td>0.34902 0.35939</td>
<td>5000</td>
<td>Green</td>
<td>D50 simulator, Sylvania F40 Design 50</td>
</tr>
<tr>
<td>F9</td>
<td>0.37417 0.37281</td>
<td>0.37829 0.37045</td>
<td>4150</td>
<td>Green</td>
<td>Cool White Deluxe Fluorescent</td>
</tr>
<tr>
<td>F10</td>
<td>0.34609 0.35866</td>
<td>0.35090 0.35444</td>
<td>5000</td>
<td>Green</td>
<td>Philips TL85, Ultralume 50</td>
</tr>
<tr>
<td>F11</td>
<td>0.38052 0.37713</td>
<td>0.38541 0.37123</td>
<td>4000</td>
<td>Green</td>
<td>Philips TL84, Ultralume 40</td>
</tr>
<tr>
<td>F12</td>
<td>0.43695 0.40441</td>
<td>0.44256 0.39717</td>
<td>3000</td>
<td>Green</td>
<td>Philips TL83, Ultralume 30</td>
</tr>
</tbody>
</table>
Why is this important?

• The color measured by a camera depends on
  – The camera response function
  – Spectrum of illuminant
  – Reflectance properties of objects in the scene

• The “color” of an object does not actually make a lot of sense, unless you talk about it under a reference light
RGB color model

- Based on human perception of colors
Color receptors

“Red” cone  “Green” cone  “Blue” cone

Response of $k$th cone $= \int \rho_k(\lambda) E(\lambda) d\lambda$
There are three types of cones
S: Short wave lengths (Blue)
M: Mid wave lengths (Green)
L: Long wave lengths (Red)

- Three attributes to a color
- Three numbers to describe a color
Color matching experiment

4.10 THE COLOR-MATCHING EXPERIMENT. The observer views a bipartite field and adjusts the intensities of the three primary lights to match the appearance of the test light. (A) A top view of the experimental apparatus. (B) The appearance of the stimuli to the observer. After Judd and Wyszecki, 1975.

Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Slide from T. Darrel
Color matching experiment

• Appearance of the stimuli to the observer

Not on a computer screen
Color matching experiment 1

Slide from T. Darrel
Color matching experiment 1

Slide from T. Darrel
Color matching experiment 1

Slide from T. Darrel
Color matching experiment 1

The primary color amounts needed for a match

Slide from T. Darrel
Color matching experiment 2

Slide from T. Darrel
Color matching experiment 2

Slide from T. Darrel
Color matching experiment 2

Slide from T. Darrel
Color matching experiment 2

We say a “negative” amount of $p_2$ was needed to make the match, because we added it to the test color’s side.

The primary color amounts needed for a match:

Slide from T. Darrel
Color matching experiment results

• Three primaries will work for most people if we allow subtractive matching
  – Exceptional people can match with two or only one primary
  – This could be caused by a variety of deficiencies
• Most people make the same matches
  – There are some anomalous trichromats, who use three primaries but make different combinations to match
Color matching functions

• Choose primaries, say $P_1(\lambda)$, $P_2(\lambda)$, $P_3(\lambda)$
• For monochromatic (single wavelength) energy function, what amounts of primaries will match it?
• That is, for each wavelength $\lambda$, determine how much of $P_1$, $P_2$, and $P_3$ is needed to match light of that wavelength alone
• These are color matching functions
RGB

- Primaries are monochromatic, energies are 645.2 nm, 526.3 nm, and 444.4 nm
- Color matching functions have negative parts
  - Some colors can be matched only subtractively
CIE XYZ

• Color matching functions are positive everywhere, but primaries are imaginary (i.e., not visible colors)
Human eye, RGB sensor, and hyperspectral sensor

Cone responses
RGB-like image channels
Hyperspectral image channels
Image channels to XYZ

Calculation of XYZ image channels: 

- Spectral distribution of the light reflected from the specimen (apple) 
- Illumination 
- Color signal 
- Sensor spectral sensitivity corresponding to the human eye

\[
I \times A = X, Y, Z
\]

I have sensors with spectral sensitivity built in.
I have data for spectral sensitivity in memory.
Hyperspectral to RGB

1. Hyperspectral to XYZ (for each pixel)

\[
X = \sum_{\lambda} \text{spd}_{\text{ill}}(\lambda) \bar{x}(\lambda) I_{\text{HSI}}(\lambda)
\]

\[
Y = \sum_{\lambda} \text{spd}_{\text{ill}}(\lambda) \bar{y}(\lambda) I_{\text{HSI}}(\lambda)
\]

\[
Z = \sum_{\lambda} \text{spd}_{\text{ill}}(\lambda) \bar{z}(\lambda) I_{\text{HSI}}(\lambda)
\]

where \(\text{spd}_{\text{ill}}(\lambda)\) is the relative spectral power distribution (SPD) function of the illuminant, and \(\bar{x}(\lambda)\), \(\bar{y}(\lambda)\), and \(\bar{z}(\lambda)\) are the CIE color matching functions

For example, use the values in [https://files.cie.co.at/204.xls](https://files.cie.co.at/204.xls) to create lookup tables (LUTs) for:

- The relative spectral power distribution (SPD) function of CIE standard illuminant D65 at a given wavelength
- The CIE 1931 standard colorimetric observer color matching functions at a given wavelength
Hyperspectral to RGB

In matrix form

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = s \begin{bmatrix}
\text{spd}_{\text{ill}}(\lambda_1)\bar{x}(\lambda_1) & \cdots & \text{spd}_{\text{ill}}(\lambda_n)\bar{x}(\lambda_n) \\
\text{spd}_{\text{ill}}(\lambda_1)\bar{y}(\lambda_1) & \cdots & \text{spd}_{\text{ill}}(\lambda_n)\bar{y}(\lambda_n) \\
\text{spd}_{\text{ill}}(\lambda_1)\bar{z}(\lambda_1) & \cdots & \text{spd}_{\text{ill}}(\lambda_n)\bar{z}(\lambda_n)
\end{bmatrix} \begin{bmatrix}
I_{\text{HSI}}(\lambda_1) \\
\vdots \\
I_{\text{HSI}}(\lambda_n)
\end{bmatrix}
\]

The scale \( s \) of the \( 3 \times n \) matrix \( M_{\text{HSI,XYZ}} \) that maps HSI to XYZ must be such that white maps to \( Y = 1 \) (i.e., the middle row sums to 1)

\[
\begin{bmatrix}
X \\
1 \\
Z
\end{bmatrix} = \frac{1}{\sum_{i=1}^{n} \text{spd}_{\text{ill}}(\lambda_i)\bar{y}(\lambda_i)} \begin{bmatrix}
\text{spd}_{\text{ill}}(\lambda_1)\bar{x}(\lambda_1) & \cdots & \text{spd}_{\text{ill}}(\lambda_n)\bar{x}(\lambda_n) \\
\text{spd}_{\text{ill}}(\lambda_1)\bar{y}(\lambda_1) & \cdots & \text{spd}_{\text{ill}}(\lambda_n)\bar{y}(\lambda_n) \\
\text{spd}_{\text{ill}}(\lambda_1)\bar{z}(\lambda_1) & \cdots & \text{spd}_{\text{ill}}(\lambda_n)\bar{z}(\lambda_n)
\end{bmatrix} \begin{bmatrix}
1 \\
\vdots \\
1
\end{bmatrix}
\]

\[
\begin{bmatrix}
X \\
1 \\
Z
\end{bmatrix} = M_{\text{HSI,XYZ}} \begin{bmatrix}
1 \\
\vdots \\
1
\end{bmatrix}
\]

where

\[
M_{\text{HSI,XYZ}} = \frac{1}{\sum_{i=1}^{n} \text{spd}_{\text{ill}}(\lambda_i)\bar{y}(\lambda_i)} \begin{bmatrix}
\text{spd}_{\text{ill}}(\lambda_1)\bar{x}(\lambda_1) & \cdots & \text{spd}_{\text{ill}}(\lambda_n)\bar{x}(\lambda_n) \\
\text{spd}_{\text{ill}}(\lambda_1)\bar{y}(\lambda_1) & \cdots & \text{spd}_{\text{ill}}(\lambda_n)\bar{y}(\lambda_n) \\
\text{spd}_{\text{ill}}(\lambda_1)\bar{z}(\lambda_1) & \cdots & \text{spd}_{\text{ill}}(\lambda_n)\bar{z}(\lambda_n)
\end{bmatrix}
\]
Hyperspectral to RGB

2. Hyperspectral to RGB

\[
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix} = M_{XYZ,RGB} M_{HSI,XYZ} \begin{bmatrix}
I_{HSI}(\lambda_1) \\
\vdots \\
I_{HSI}(\lambda_n)
\end{bmatrix}
\]

\[
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix} = M_{HSI,RGB} \begin{bmatrix}
I_{HSI}(\lambda_1) \\
\vdots \\
I_{HSI}(\lambda_n)
\end{bmatrix}
\]

where

\[
M_{HSI,RGB} = M_{XYZ,RGB} M_{HSI,XYZ}
\]

See lecture 2
Example

• 31 bands
  – 410 nm to 710 nm, 10 nm increments
• CIE Standard Illuminant D65
  – The standard daylight illuminant
Example

410 nm
Example

420 nm
Example

430 nm
Example

440 nm
Example

450 nm
Example

460 nm
Example

470 nm
Example

480 nm
Example

490 nm
Example

500 nm
Example

510 nm
Example

520 nm
Example

530 nm
Example

540 nm
Example

550 nm
Example

560 nm
Example

570 nm
Example

CSE 273, Winter 2024
Example

590 nm
Example

600 nm
Example

610 nm
Example

620 nm
Example

630 nm
Example

640 nm
Example

650 nm
Example

660 nm
Example

670 nm
Example

680 nm
Example

![Building Image]

690 nm
Example

700 nm
Example

710 nm
Example

Result

RGB image
Hyperspectral to RGB

• Only dependent on the relative spectral power distribution (SPD) function of the illuminant and the CIE color matching functions (which are related to the human visual system)

• Linear transformation
  – Matrix-vector multiply

• Useful for visualization to a human and image registration
Next lecture

• Image processing