EE3414

Multimedia Communication Systems - I

Basics of Color Imaging

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Outline

• Color perception and specification
  – Color as EM waves
  – Human perception of color
  – Trichromatic color mixing theory
• Different color representations
  – Primary color (RGB, CMY)
  – Luminance/chrominance
• Color image capture and display
  – 3D to 2D projection
  – Analog vs. digital camera
• Color quantization
  – Uniform
  – Adaptive
  – Dithering
Light is part of the EM wave

FIGURE 6.2  Wavelengths comprising the visible range of the electromagnetic spectrum. (Courtesy of the General Electric Co., Lamp Business Division.)

Color images with figure captions in this and following slides are from [Gonzalez02]
Illuminating and Reflecting Light

• Illuminating sources:
  – emit light (e.g. the sun, light bulb, TV monitors)
  – perceived color depends on the emitted freq.
  – follows additive rule: R+G+B=White

• Reflecting sources:
  – reflect an incoming light (e.g. the color dye, matte surface, cloth)
  – perceived color depends on reflected freq (=emitted freq-absorbed freq.)
  – follows subtractive rule: R+G+B=Black
Eye Anatomy

From http://www.stlukeseye.com/Anatomy.asp
## Eye vs. Camera

<table>
<thead>
<tr>
<th>Camera components</th>
<th>Eye components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lens</td>
<td>Lens, cornea</td>
</tr>
<tr>
<td>Shutter</td>
<td>Iris, pupil</td>
</tr>
<tr>
<td>Film</td>
<td>Retina</td>
</tr>
<tr>
<td>Cable to transfer images</td>
<td>Optic nerve send the info to the brain</td>
</tr>
</tbody>
</table>
Human Perception of Color

- Retina contains photo receptors
  - Cones: day vision, can perceive color tone
    - Red, green, and blue cones
    - Different cones have different frequency responses
    - Tri-receptor theory of color vision [Young1802]
  - Rods: night vision, perceive brightness only

- Color sensation is characterized by
  - Luminance (brightness)
  - Chrominance
    - Hue (color tone)
    - Saturation (color purity)

From http://www.macula.org/anatomy/retinaframe.html
Frequency Responses of Cones

\[ C_i = \int C(\lambda) a_i(\lambda) d\lambda, \quad i = r, g, b, y \]
Trichromatic Color Mixing

- Trichromatic color mixing theory
  - Any color can be obtained by mixing three primary colors with a right proportion
- Primary colors for illuminating sources:
  - Red, Green, Blue (RGB)
  - Color monitor works by exciting red, green, blue phosphors using separate electronic guns
  - follows additive rule: $R+G+B=\text{White}$
- Primary colors for reflecting sources (also known as secondary colors):
  - Cyan, Magenta, Yellow (CMY)
  - Color printer works by using cyan, magenta, yellow and black (CMYK) dyes
  - follows subtractive rule: $R+G+B=\text{Black}$
RGB vs CMY

Magenta = Red + Blue
Cyan = Blue + Green
Yellow = Green + Red

Magenta = White - Green
Cyan = White - Red
Yellow = White - Blue
Color Specification

- Specify three primary or secondary colors
  - RGB
  - CMY
- Specify the luminance and chrominance
  - HSB or HSI (Hue, saturation, and brightness or intensity)
  - YIQ (used in NTSC color TV)
  - YCbCr (used in digital color TV)
- Amplitude specification:
  - 8 bits for each color component, or 24 bits total for each pixel
  - Total of 16 million colors
  - A true RGB color display of size 1Kx1K requires a display buffer memory size of 3 MB
RGB Coordinate

**FIGURE 6.7**
Schematic of the RGB color cube. Points along the main diagonal have gray values from black at the origin to white at point (1, 1, 1).

**FIGURE 6.8** RGB 24-bit color cube.
Color Conversion

Some important color coordinates (RGB, CMY, XYZ, YIQ, etc) can be converted from each other using linear conversion.

Ex: RGB <-> YIQ:

\[
\begin{bmatrix}
\tilde{R} \\
\tilde{G} \\
\tilde{B}
\end{bmatrix} = \begin{bmatrix}
1.000 & 0.956 & 0.620 \\
1.000 & -0.272 & -0.647 \\
1.000 & -1.108 & 1.700
\end{bmatrix} \begin{bmatrix}
Y \\
I \\
Q
\end{bmatrix}
\]

Ex: RGB <-> CMY:

\[
\begin{bmatrix}
C \\
M \\
Y
\end{bmatrix} = \begin{bmatrix}
255 \\
255 \\
255
\end{bmatrix} - \begin{bmatrix}
\tilde{R} \\
\tilde{G} \\
\tilde{B}
\end{bmatrix}
\]
Demo Using Photoshop

• Show the RGB, CMY, HS I models
  – Using the “window>show color” tool (in “show color”, click on right arrow button to choose different color sliders)
  – Sample image: RGBadd, CMYsub
    • Use the dropper tool, click on different part of the image, see the color information in “show color”
    • Select different color coordinates
Image Capture

- For natural images we need a light source \( (\lambda: \text{wavelength of the source}) \):
  \(- E(x, y, z, \lambda): \) incident light on a point \((x, y, z \text{ world coordinates of the point})\)

- Each point in the scene has a reflectivity function.
  \(- r(x, y, z, \lambda): \) reflectivity function

- Light reflects from a point and the reflected light is captured by an imaging device.
  \(- c(x, y, z, \lambda) = E(x, y, z, \lambda) \times r(x, y, z, \lambda): \) reflected light.

\[
\begin{align*}
\rightarrow & \quad E(x, y, z, \lambda) \\
\rightarrow & \quad c(x, y, z, \lambda) = E(x, y, z, \lambda) \cdot r(x, y, z, \lambda)
\end{align*}
\]

\[\text{Camera}(c(x, y, z, \lambda)) = \text{ }\]

Courtesy of Onur Guleryuz
More on Image Capture

• Reflected light to camera
  – Camera absorption function

\[
\bar{\psi}_{R,G,B}(X, t) = \int C(X, t, \lambda) a_{R,G,B}(\lambda) d\lambda
\]

• A color camera has three color filters
• \(a_{R,G,B}\) reflects the frequency response of each color filter

– Projection from 3-D to 2-D

\[
X \rightarrow_P x
\]

\[
\psi_{R,G,B}(x, t) = \bar{\psi}_{R,G,B}(X, t)
\]
The image of an object is reversed from its 3-D position. The object appears smaller when it is farther away.
Color Image Capture

- Need three color filters: absorbing the red, green, and blue components separately
- Analog camera: a continuous image is projected onto a film from the lens
- Digital camera:
  - An CCD array captures the three color intensity at every pixel
  - The color values for all the pixels are directly saved in a memory card – In the no-compression mode
    - A 2-Mega pixel image (1600x1200) takes 5.7 Mbytes
    - A 3-Mega pixel image (2048x1536) takes 9.4 MBytes
  - The image is compressed and then saved
    - JPEG is the standard coding method used in digital cameras
    - Typical compression ratio (with high quality): 10-15
Color Image Display

- **Red signal**
  - Red LUT
  - Red Gun
- **Green signal**
  - Green LUT
  - Green Gun
- **Blue signal**
  - Blue LUT
  - Blue Gun

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
</tr>
<tr>
<td>255</td>
<td></td>
</tr>
</tbody>
</table>
Color Image Display and Printing

• Display:
  – Need three light sources projecting red, green, blue components respectively at every pixel. This is realized by exciting the phosphors behind the screen with electronic beams with appropriate intensity. There are three types of phosphors, one for each color.
  – Analog display: electronic beams cover the entire screen by raster scan
  – Digital display: directly exciting at all pixel locations

• Printing:
  – Need three (or more) color dyes (Cyan, Magenta, Yellow, and Black)
  – Out of gamut color: replaced by the nearest color
Each color model has different color range (or gamut). RGB model has a larger gamut than CMY. Therefore, some color that appears on a screen may not be printable and is replaced by the closest color in the CMY gamut.
Demo with Photoshop

- Using photoshop to show how to replace a out of gamut color by its closest in-gamut color.
- Choose “window->show color”, choose the “CMYK slider”
- While having “RGBadd” in display, use dropper to click on “red”, “green” or “blue”, you will see a warning about out of gamut color, and the suggested replacement color
- Also open “gamut” image, click on out of gamut region
Color Quantization

- Select a set of colors that are most frequently used in an image, save them in a look-up table (also known as color map or color palette)
- Any color is quantized to one of the indexed colors
- Only needs to save the index as the image pixel value and in the display buffer
- Typically: $k=8$, $m=8$ (selecting 256 out of 16 million colors)

<table>
<thead>
<tr>
<th>Input index (k bits)</th>
<th>Red color (m bits)</th>
<th>Green color (m bits)</th>
<th>Blue color (m bits)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Index 1</td>
<td>…</td>
<td>…</td>
<td>…</td>
</tr>
<tr>
<td>……</td>
<td>…</td>
<td>…</td>
<td>…</td>
</tr>
<tr>
<td>Index $2^k$</td>
<td>…</td>
<td>…</td>
<td>…</td>
</tr>
</tbody>
</table>
Uniform vs. Adaptive Quantization

• Uniform (scalar quantization)
  – Quantize each color component uniformly
    • E.g. 24 bit-> 8 bit can be realized by using 3 bits (8 levels) for red, 3 bits (8 levels) for green, 2 bits (4 levels) for blue
    • Do not produce good result

• Adaptive (vector quantization)
  – Treating each color (a 3-D vector) as one entity. Finds the $N$ colors (vectors) that appear most often in a given image, save them in the color palette (codebook). Replace the color at each pixel by the closest color in the codebook
  – The codebook (i.e. color palette) varies from image to image - > adaptive
24 bits -> 8 bits

Adaptive (non-uniform) quantization
(vector quantization)

Uniform quantization
(3 bits for R, G, 2 bits for B)
Web Colors: 216 Safe RGB Colors

These colors are those that can be rendered consistently by different computer systems. They are obtained by quantizing the R,G,B component independently using uniform quantization. Each component is quantized to 6 possible values: 0, 51, 102, 153, 204, 255.
Color Dithering

- Color quantization may cause contour effect when the number of colors is not sufficient
- Dithering: randomly perturb the color values slightly to break up the contour effect
  - fixed pattern dithering
  - diffusion dithering (the perturbed value of the next pixel depends on the previous one)
  - Developed originally for rendering gray scale image using black and white ink only

![Diagram of color dithering](chart.png)
8 bit uniform without dithering

8 bit uniform with diffusion dithering
Demo Using Photoshop

- Show quantization results with different methods using “image->mode->index color”
- Use my test image “anna_color”
Pseudo Color Display

• Why?
  – Human eye is more sensitive to changes in the color hue than in brightness.

• How?
  – Use different colors (different in hue) to represent different image features in a monochrome image.
  – **Intensity slicing**: Display different gray levels as different colors
    • Can be useful to visualize medical / scientific / vegetation imagery
    • E.g. if one is interested in features with a certain intensity range or several intensity ranges

  – **Frequency slicing**: Decomposing an image into different frequency components and represent them using different colors.
Intensity Slicing

Pixels with gray-scale (intensity) value in the range of \((f_{i-1}, f_i)\) are rendered with color \(C_i\)
Example

**FIGURE 6.20** (a) Monochrome image of the Picker Thyroid Phantom. (b) Result of density slicing into eight colors. (Courtesy of Dr. J. L. Blankenship, Instrumentation and Controls Division, Oak Ridge National Laboratory.)
Another Example

**Figure 6.22** (a) Gray-scale image in which intensity (in the lighter horizontal band shown) corresponds to average monthly rainfall. (b) Colors assigned to intensity values. (c) Color-coded image. (d) Zoom of the South America region. (Courtesy of NASA.)
Pseudo Color Display of Multiple Images

- Display multi-sensor images as a single color image
  - Multi-sensor images: e.g. multi-spectral images by satellite

**FIGURE 6.26** A pseudocolor coding approach used when several monochrome images are available.
An Example

**FIGURE 6.27** (a)–(d) Images in bands 1–4 in Fig. 1.10 (see Table 1.1). (e) Color composite image obtained by treating (a), (b), and (c) as the red, green, blue components of an RGB image. (f) Image obtained in the same manner, but using in the red channel the near-infrared image in (d). (Original multispectral images courtesy of NASA.)
Example

FIGURE 6.28
(a) Pseudocolor rendition of Jupiter Moon Io.
(b) A close-up.
(Courtesy of NASA.)
What Should You Know

• Each color is an EM wave at a certain wavelength in the visible light band
• How a human perceives color
  – Three types of cones sensitive to red, green, and blue respectively
• How to generate different colors in display and in printing
  – By mixing three primary colors
  – RGB for display, CMY+K for printing
• How is a color image stored
  – Consists of three separate component images: ex. R,G,B, YCbCr
• A camera or eye project a 3D scene to a 2D image
  – Can be modeled by the perspective projection
• Color quantization
  – True color vs. index color image
  – Uniform scalar quantization, vector quantization, dithering
• Pesudo color display
References