Color Image Processing

Background

- Humans can perceive thousands of colors, and only about a couple of dozen gray shades (cones/rods)
- Divide into two major areas: full color and pseudo color processing
  - Full color – Image is acquired with a full-color sensor like TV camera or color scanner
  - Pseudo color – Assign a color to a range of monochrome intensities
  - The availability of inexpensive and powerful hardware has resulted in the proliferation of applications based on full color processing
- 8-bit color vs 24-bit color
  - Color quantization
- Some of the gray scale image processing methods are directly applicable to color processing but others will need reformation

Color fundamentals

- Color spectrum/prism
  - Figure 6.1
  - White light divided into different colors
  - Colors blend into each other smoothly (Figure 6.2)
- Color – Perceptual result of light in the visible region of spectrum as incident on the retina
  - 400 nm to 700 nm
  - Visible light is a narrow band of frequencies in the electromagnetic spectrum (Figure 6.2)
  - White light is result of reflected light balanced across all visible wavelengths
  - Reflectance from a body in limited range of visible spectrum is perceived as color
    - Green objects reflect light with wavelength in the 500-570nm range while absorbing other wavelengths
- Characterization of light
  - Achromatic (no color) or monochromatic light characterized by intensity
  - Gray level as a scalar measure of intensity from black to white
- Chromatic light
  - Spans the electromagnetic spectrum from approximately 400–700 nm
  - Light source characterized by three quantities
    - Radiance: Total amount of energy emitted by light source, measured in watts
      - Physical power of light energy
      - Measures the quantity of radiation that passes through or emitted from a surface and falls within a given solid angle in a specified direction
      - Expressed in a spectral power distribution, often in 31 components, each representing a 10 nm band
    - Brightness: Achromatic notion of intensity to describe color sensation
      - Attribute of a visual sensation according to which an area appears to emit more or less light
      - Cannot be measured quantitatively
**Luminance**  Measure of amount of energy as perceived by an observer, measured in lumens or candelas per square meter

* More tractable version of brightness, defined by CIE
* Radiant power weighted by a spectral sensitivity function that is characteristic of vision
* Luminous efficiency peaks at 555nm
* CIE luminance, denoted by $Y$, is the integral of spectral power distribution, using spectral sensitivity curve as a weighting function
* Magnitude of luminance is proportional to physical power, but spectral composition is related to brightness sensitivity of human vision
* Units of measurement for image processing
  - Normalized to 1 or 100 with respect to a standard white reference
  - $Y = 1$ is the white reference of a studio broadcast monitor whose luminance is 80 cd/m$^2$

- Cones in the eye respond to three colors: red, green, blue
  - 6 to 7 million cones in human eye
  - 65% cones respond to red eye
  - 33% cones respond to green light
  - 2% cones respond to blue light, these being most sensitive
  - Figure 6-03
  - Red, green, and blue are known as primary colors
    - In 1931, CIE designated specific wavelengths for primary colors
      - Red – 700nm
      - Green – 546.1nm
      - Blue – 435.8nm
    - To generate all colors, we may have to vary the wavelengths of primary colors while mixing colors; so the three primary colors are neither fixed nor standard
    - The curves in Fig 6.3 indicate that a single color may be called red, green, or blue

- Secondary colors
  - Created by adding primary colors
    - Cyan = Green + Blue
    - Magenta = Red + Blue
    - Yellow = Red + Green
  - Mixing all three primary colors produces white
    - Fig 6-04
    - The secondary colors are primary colors of pigments, which have red, green, and blue as secondary colors

- How do we represent black? Absence of color.
  - While printing, we need to print black on white
  - Subtractive colors based on pigments
    - Primary color of a pigment is defined as one that absorbs a primary color of light and transmits the other two
    - Given by cyan, magenta, yellow (CMY)
  - A secondary combined with its opposite primary produces black

- Color TV reception
  - Characterized by additive nature of colors
    - Large array of triangular dot patterns of electron sensitive phosphor
    - Intensity of individual phosphors modulated by electron gun, one corresponding to each primary color
  - The same technology is used in the flat panel displays, using three subpixels to generate a color pixel

- Color characterized by three quantities
Hue Dominant color as perceived by an observer (red, orange, or yellow)

Saturation Relative purity of color; pure spectrum colors are fully saturated
  * Saturation is inversely proportional to the amount of white light added

Brightness Achromatic notion of intensity

- Chromaticity
  * Combination of hue and saturation
  * Allows a color to be expressed as its brightness and chromaticity

- Tristimulus values
  * Three types of cones in the eye require three components for each color, using appropriate spectral weighting functions
    - Based on standard curves/functions defined by CIE – Commission Internationale de L’Eclairage
    - Curves specify the transformation of spectral power distribution for each color into three numbers
  * Amount of red, green, and blue to express a color
  * Denoted by \( X \), \( Y \), and \( Z \)
  * Color specified by its tristimulus coefficients

\[
x = \frac{X}{X + Y + Z}
\]
\[
y = \frac{Y}{X + Y + Z}
\]
\[
z = \frac{Z}{X + Y + Z}
\]

* Note that \( x + y + z = 1 \)

- Chromaticity diagram
  * Figure 6-05
  * Color given as a function of \( x \) and \( y \)
  * The corresponding value of \( z \) is obtained by \( 1 - (x + y) \)
  * Points on the boundary are fully saturated colors
  * Saturation at point of equal energy is 0
  * Mainly useful for color mixing
    - Any straight line joining two points defines all the color variations obtained by combining the two colors additively
    - Extension to three colors by using a triangle to connect three points
    - Supports the assertion that not all colors can be obtained with three single, fixed primaries as some of them are outside the triangle
    - Figure 6-06 – Color gamut

Color models

- Also called color space or color system
- Allow the specification of colors in some standard way
- Specification of a coordinate system and a subspace within that system
  - Each color represented by a single point
- Models oriented towards hardware (rendering and scanning) or software (reasoning and applications)
- RGB color model
- Figure 6-07
- Unit cube
  * Based on Cartesian coordinate system
  * All color values are assumed to be normalized to the range [0,1]
  * Colors defined by vectors extending from origin; origin represents black
  * RGB primaries are at the corners that are neighbors to the origin; other corners (at distance 2 from origin) represent secondary colors (CMY)
  * Corner opposite to origin, given by point (1,1,1), represents white
  * Different shades of gray are distributed along the cube diagonal from black to white corners
- Pixel depth – Number of bits used to represent each pixel in RGB space
  * Depth of 24-bits when each color represented by 8 bits in the triplet to represent pixel
- Figure 6-08
- Rendering an image
  * Images consist of three component images, one for each primary color
- Figure 6-09
  * Fuse the three color components together
- Acquiring an image
  * Figure 6-09, but in reverse
  * Acquire individual color planes and put them together
- Does not make sense to use all the possible $2^{24}$ colors in 24-bit space
  * Safe colors
    - Can be reproduced on a variety of devices
    - Likely to be reproduced faithfully, reasonably independent of hardware capabilities
  * Safe RGB colors or safe browser colors
    - Number of colors that can be reproduced faithfully in any system – 256
    - 40 of these colors are known to be processed differently by different OSs
    - Number of colors common to most systems – 216
  * Safe RGB color values
    - Formed from 6 possible values of each component as follows
    - Each successive color is 51 (0x33) more than its predecessor
    - Triplets give $6^3 = 216$ possible values
- Figure 6-10
    - Not all possible 8-bit gray colors are included in the set of 216 colors
    - RGB safe-color cube – Figure 6.11
    - Color safe cube has valid colors only on the surface

- CMY and CMYK color models

  * CMY and CMYK color models
  * Primary colors of pigments
  * Pigments subtract light rather than radiate light
    * Illuminating a surface coated with cyan pigment absorbs red component of light
  * Devices that deposit color pigments on paper perform an RGB to CMY conversion internally by a simple operation

\[
\begin{bmatrix}
C \\
M \\
Y \\
\end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix}
\]
Equal contribution of cyan, magenta, and yellow should produce black but in practice, it produces muddy-looking black

- A fourth color is added, yielding CMYK system

**HSI color model**

- **Hue, saturation, intensity**

- **RGB and CMY models**
  - Ideally suited for hardware implementation
  - RGB matches the human eye’s perception for primary colors
  - RGB and CMY not suitable for describing colors for human interpretation
  - Dark or light or pastel colors
  - Humans do not think of color images as being composed of three primary images that form a single images

- **Human description of images/colors**
  - In terms of hue, saturation, and brightness

- **HSI model** decouples intensity component from the color-carrying components (hue and saturation)
  - Ideal tool for developing image processing algorithms
  - Natural and intuitive to humans

- **Intensity**
  - Measure over some interval of the electromagnetic spectrum of the flow of power that is radiated from, or incident on, a surface
  - Linear light measure, expressed in units such as watts per square meter
  - Controlled on a CRT monitor by voltages presented, in a nonlinear manner for each color component
  - CRT voltages are not proportional to intensity
  - RGB color images can be viewed as three monochrome intensity images
  - Extracting intensity from RGB images
    - Stand the RGB color cube on the black vertex, with white vertex directly above it (Figure 6.12a)
    - Line joining the black and white vertices is now vertical
    - Intensity of any color given by intersection of intensity axis and a plane perpendicular to it and intersecting with the color point in cube
    - Saturation of color increases as a function of distance from intensity axis
    - Saturation of points along intensity axis is zero (all points on intensity axis are gray)

- **Hue**
  - Consider the plane defined by black, white, and cyan (Figure 6.12b)
  - Intensity axis is contained within this plane
  - All points contained in plane segment given by these three points have the same hue – cyan
  - Rotating the plane about the intensity axis gives us different hues

- Above discussion leads us to conclude that we can convert a color from the RGB values to HSI space by working out the geometrical formulas (Figure 6.13)
  - Primary colors are separated by 120°
  - Secondary colors are 60° from the primaries
  - Hue of a point is determined by an angle from a reference point
    - By convention, reference point is taken as angle from red axis
    - Hue increases counterclockwise from red axis
  - Saturation is the length of vector from origin to the point
    - Origin is given by intensity axis

- Figure 6.14 to describe HSI model
• Converting colors from RGB to HSI
  – Consider RGB values normalized to the range [0, 1]
  – Given an RGB value, H is obtained as follows:
    \[ H = \begin{cases} \theta & \text{if } B \leq G \\ 360 - \theta & \text{if } B > G \end{cases} \]
    
    * It should be normalized to the range [0, 1] by dividing the quantity computed above by 360
  – \( \theta \) is given by
    \[ \theta = \cos^{-1} \left\{ \frac{1}{2} \left[ (R - G) + (R - B) \right] \left[ (R - G)^2 + (R - B)(G - B) \right]^{1/2} \right\} \]
    
    * \( \theta \) is measured with respect to red axis of HSI space
  – Saturation is given by
    \[ S = 1 - \frac{3}{(R + G + B)} \left[ \min(R, G, B) \right] \]
  – Intensity component is given by
    \[ I = \frac{1}{3} (R + G + B) \]

• Converting colors from HSI to RGB
  – Consider the values of HSI in the interval [0, 1]
  – \( H \) should be multiplied by 360 (or \( 2\pi \)) to recover the angle; further computation is based on the value of \( H \)
  – RG sector \( 0^\circ \leq H < 120^\circ \)
    \[ B = I(1 - S) \]
    \[ R = I \left[ 1 + \frac{S \cos H}{\cos(60^\circ - H)} \right] \]
    \[ G = 3I - (R + B) \]
  – GB sector \( 120^\circ \leq H < 240^\circ \)
    \[ H' = H - 120^\circ \]
    \[ R = I(1 - S) \]
    \[ G = I \left[ 1 + \frac{S \cos H'}{\cos(60^\circ - H')} \right] \]
    \[ B = 3I - (R + G) \]
  – BR sector \( 0^\circ \leq H < 360^\circ \)
    \[ H' = H - 240^\circ \]
    \[ G = I(1 - S) \]
    \[ B = I \left[ 1 + \frac{S \cos H'}{\cos(60^\circ - H')} \right] \]
    \[ R = 3I - (G + B) \]

• Figure 6.15
  – HSI components of RGB cube, plotted separately
  – Discontinuity along the 45° line in the hue figure
    * See the reason by going around the middle in Figure 6.8
Saturation image shows progressively darker values close to the white vertex of RGB cube
Intensity is simply the average of RGB values at the corresponding pixel

- Manipulating HSI component images
  - Figure 6.16 – image composed of primary and secondary RGB colors and their HSI equivalents
    * In hue, red region maps to black as its angle is 0°
    * In b, c, and d parts of the image, the pixels are scaled to the range [0,1]
  - Individual colors changed by changing the hue image
  - Purity of colors changed by varying the saturation
  - Figure 6.17a – Change blue and green pixels in Figure 6.16a to 0 (compare with Figure 6.16b)
  - Figure 6.17b – Change saturation of cyan component in Figure 6.16c to half
  - Figure 6.17c – Reduce the intensity of central white region in Figure 6.16d by half
  - Figure 6.17d – Combine the three HSI components back into RGB image

HSV color space

- Projects the RGB color cube onto a non-linear chroma angle (H), a radial saturation percentage (S), and a luminance-inspired value (V)
- Similar to HSI color space

Pseudocolor image processing

- Assign colors to gray values based on a fixed criteria
- Used as an aid to human visualization and interpretation of gray-scale events in an image or sequence of images, such as visualizing population density in different areas on a map
- May have nothing to do with processing of true color images
- Intensity slicing
  - Also called density slicing or color coding
  - Slicing planes parallel to horizontal plane in 3D space, with the intensity of image providing the third dimension on image plane
    * Figure 6.18
    * Plane at \( f(x, y) = l_i \) to slice the image function into two levels
    * Assign different colors to area on different sides of the slicing plane
    * Relative appearance of the resulting image manipulated by moving the slicing plane up and down the gray-level axis
  - Technique summary
    * Gray scale representation – [0, \( L - 1 \)]
    * Black represented by \( l_0, [f(x, y) = 0] \)
    * White represented by \( [L - 1], [f(x, y) = L - 1] \)
    * Define \( P \) planes perpendicular to intensity axis at levels \( l_1, l_2, \ldots, l_P \)
    * 0 < \( P < L - 1 \)
    * \( P \) planes partition the gray scale into \( P + 1 \) intervals as \( V_1, V_2, \ldots, V_{P+1} \)
* Make gray-level to color assignment as

\[ f(x, y) = c_k \text{ if } f(x, y) \in V_k \]

where \( c_k \) is the color associated with \( k \)th intensity interval \( V_k \) defined by partitioning planes at \( l = k - 1 \) and \( l = k \).

- Alternative mapping function to intensity slicing planes
  - Figure 6.19
  - Staircase form of mapping with multiple levels
- Figure 6.20 – Picker Thyroid Phantom (radiation test pattern)
  - Intensity slicing image into eight color regions
  - Idea is to make it easy to distinguish between shades without assigning any semantic interpretation to the color
- Figure 6.21 – Cracks in weld seen through X-ray image
  - Full strength of X-rays passing through is assigned one color; everything else a different color
- Figure 6.22 – Measurement of rainfall levels

- Gray level to color transformations
  - Separate independent transformation of gray level inputs to three colors
  - Figure 6.23
  - Composite image with color content modulated by nature of transformation function
  - Piecewise linear functions of gray levels
  - Figure 6.24 – Luggage through X-ray scanning system
    - Image on right contains a block of simulated plastic explosives
    - Figure 6.25 – Transformation functions used
    - Emphasize ranges in gray scale by changing sinusoidal frequencies

- Combining several monochrome images into a single color composite
  - Figure 6.26
  - Used in multispectral image processing, with different sensors producing individual monochrome images in different spectral bands
  - Figure 6.27
    - Images of Washington, DC, and Potomac river in red, green, blue, and near IR bands
    - Image \( f \) generated by replacing the red component of image \( e \) by NIR image
      - NIR strongly responsive to biomass component
    - Image \( f \) shows the difference between biomass (red) and man-made features such as concrete and asphalt (bluish green)
  - Figure 6.28
    - Jupiter moon Io, using images in several spectral regions by the spacecraft Galileo
    - Bright red depicts material recently ejected from an active volcano while surrounding yellow shows older sulfur deposits

**Basics of full-color image processing**

- Two major categories of processing
  1. Process each component of image (RGB or HSI) individually and then form a composite processed color image
– Each component can be processed using gray-scale processing techniques

2. Work with color pixels directly, treating each pixel as a vector

\[
c = \begin{bmatrix} c_R \\ c_G \\ c_B \end{bmatrix} = \begin{bmatrix} R \\ G \\ B \end{bmatrix}
\]

– Since each pixel is a function of coordinates \((x, y)\), we have

\[
c(x, y) = \begin{bmatrix} c_{R}(x, y) \\ c_{G}(x, y) \\ c_{B}(x, y) \end{bmatrix} = \begin{bmatrix} R(x, y) \\ G(x, y) \\ B(x, y) \end{bmatrix}
\]

– Each component of the vector is a spatial variable in \(x\) and \(y\)

– For an \(M \times N\) image, there are \(MN\) vectors \(c(x, y)\) for \(x = 0, 1, 2, \ldots, M - 1\) and \(y = 0, 1, 2, \ldots, N - 1\)

• The two methods may or may not produce equivalent results
  – Scalar versus vector operations
    * The process used should be applicable to both scalars and vectors
    * The operation on each component of the vector must be independent of the other components
  – Neighborhood processing will be an example where we get different results (Figure 6.29)
    * Averaging the images separately in individual planes and averaging the vectors will give different results

**Color transformations**

• Process the components of a color image within the context of a single color model, without converting components to different color space

• Think of an application that needs to brighten a picture
  – Can we achieve this by adding a constant quantity to each of the three RGB channels?
  – This will not only increase the intensity of each pixel but also hue and saturation
  – A better solution will be to manipulate the luminance \(I\) to recompute a valid RGB image with the same hue and saturation

• Formulation
  – Model color transformations using the expression

\[
g(x, y) = T[f(x, y)]
\]

\(T\) is the operator over a spatial neighborhood of \((x, y)\)

– Each \(f(x, y)\) component is a triplet in the chosen color space
– Figure 6.30 – Various color components of an image
– Must consider the cost of converting from one color space to another when looking at the operations
– Modifying intensity of an image in different color spaces, using the transform

\[
g(x, y) = kf(x, y)
\]

* In HSI color space, converting a pixel \(h, s, i\) to \(h', s', i'\)

\[
h' = h
s' = s
i' = ki
\]
* In RGB color space, converting a pixel \( r, g, b \) to \( r', g', b' \):

\[
\begin{bmatrix}
  r' \\
  g' \\
  b'
\end{bmatrix} = k \cdot \begin{bmatrix}
  r \\
  g \\
  b
\end{bmatrix}
\]

* In CMY color space:

\[
c' = kc + (1 - k)
\]

\[
m' = km + (1 - k)
\]

\[
y' = ky + (1 - k)
\]

- Simple operation in HSI but cost to convert to HSI may not be justifiable
  * Figure 6.31, using \( k = 0.7 \)

- Color complements
  - Hues directly opposite one another on the color circle
    * Figure 6.32
  - Analogous to gray scale negatives
  - Can be used to enhance details buried in dark regions of an image
    * Figure 6.33
  - May not have the same saturation in negative image in HSI
    * Figure shows saturation component unaltered

- Color slicing
  - Used to highlight a specific range of colors in an image to separate objects from surroundings
  - Display just the colors of interest, or use the regions defined by specified colors for further processing
  - More complex than gray-level slicing, due to multiple dimensions for each pixel
  - Dependent on the color space chosen; I prefer HSI
  - Using a cube of width \( W \) to enclose the reference color with components \( (a_1, a_2, \ldots, a_n) \), the transformation is given by
    \[
s_i = \begin{cases} 
    0.5 & \text{if } \left| r_j - a_j \right| > \frac{W}{2} \text{ for any } 1 \leq j \leq n \\
    r_i & \text{otherwise}
    \end{cases} \quad i = 1, 2, \ldots, n
\]
  - If the color of interest is specified by a sphere of radius \( R_0 \), the transformation is
    \[
s_i = \begin{cases} 
    0.5 & \text{if } \sum_{j=1}^{n} (r_j - a_j)^2 > R_0^2 \\
    r_i & \text{otherwise}
    \end{cases} \quad i = 1, 2, \ldots, n
\]
    * Figure 6.34

- Color balancing
  - Process to compensate for incandescent lighting
  - You can perform color balancing by multiplying each channel with a different scale factor, or by mapping the pixels to XYZ color space, changing the nominal white point, and mapping back to RGB

**Tone and color corrections**

- Used for photo enhancement and color reproduction
• Device independent color model from CIE relating the color gamuts
• Use a color profile to map each device to color model

• CIE L*a*b* system
  – Most common model for color management systems
  – Components given by the following equations
    \[
    \begin{align*}
    L^* &= 116 \cdot h \left( \frac{Y}{Y_W} \right) - 16 \\
    a^* &= 500 \left[ h \left( \frac{X}{X_W} \right) - h \left( \frac{Y}{Y_W} \right) \right] \\
    b^* &= 200 \left[ h \left( \frac{Y}{Y_W} \right) - h \left( \frac{Z}{Z_W} \right) \right]
    \end{align*}
    \]
    where
    \[
    h(q) = \begin{cases} 
    q^2 & \text{if } q > 0.008856 \\
    7.787q + \frac{16}{116} & \text{otherwise}
    \end{cases}
    \]
  – \(X_W, Y_W, \) and \(Z_W\) are values for reference white, called \(D_{65}\) which is defined by \(x = 0.3127\) and \(y = 0.3290\) in the CIE chromaticity diagram
  – \(X, Y, Z\) are computed from rgb values as
    \[
    \begin{bmatrix}
    X \\ Y \\ Z
    \end{bmatrix} = 
    \begin{bmatrix}
    0.412453 & 0.357580 & 0.180423 \\
    0.212671 & 0.715160 & 0.072169 \\
    0.019334 & 0.119193 & 0.950227
    \end{bmatrix} 
    \begin{bmatrix}
    R_{709} \\ G_{709} \\ B_{709}
    \end{bmatrix}
    \]
  – Rec. 709 RGB corresponds to \(D_{65}\) white point
  – \(L^*a^*b^*\) is calorimetric, perceptually uniform, and device independent
  – \(L^*a^*b^*\) decouples intensity from color
    * \(a^*\) gives red minus green
    * \(b^*\) gives green minus blue