Digital Image Processing

Color Image Processing

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Color Image Processing

“It is only after years of preparation that the young artist should touch color – not color used descriptively, that is, but as a means of personal expression”.

Henri Matisse

“For a long time I limited myself to one color – as a form of discipline”.

Pablo Picasso
Introduction

Today we'll look at color image processing, covering:
- Color fundamentals
- Color models
- Pseudocolor image processing
- Color image smoothing and sharpening
- Color edge detection
- Noise in color images
- Color perception models

Color Fundamentals

• In 1666 Sir Isaac Newton discovered that when a beam of sunlight passes through a glass prism, the emerging beam is split into a spectrum of colors
Color Fundamentals (cont…)

• The colors that humans and most animals perceive in an object are determined by the nature of the light reflected from the object.

• For example, green objects reflect light with wavelengths primarily in the range of 500 – 570 nm while absorbing most of the energy at other wavelengths.

Color Fundamentals (cont…)

• 3 basic quantities are used to describe the quality of a chromatic light source:
  – Radiance: the total amount of energy that flows from the light source (measured in watts)
  – Luminance: the amount of energy an observer perceives from the light source (measured in lumens)
    • Note we can have high radiance, but low luminance
  – Brightness: a subjective (practically unmeasurable) notion that embodies the achromatic notion of intensity of light
### Color Fundamentals (cont…)

- Chromatic light spans the electromagnetic spectrum from approximately 400 to 700 nm.
- Human color vision is achieved through 6 to 7 million cones in each eye.

![Color Spectrum Diagram](image)

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<thead>
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<th>Wavelength (Nanometers)</th>
<th>Ultraviolet</th>
<th>Visible Spectrum</th>
<th>Infrared</th>
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</tbody>
</table>

### Color Fundamentals (cont…)

- Three principal sensing groups:
  - 66% of these cones are sensitive to red light
  - 33% to green light
  - 2% to blue light.
- Absorption curves for the different cones have been determined experimentally.
- Strangely these do not match the CIE standards for red (700nm), green (546.1nm) and blue (435.8nm) light as the standards were developed before the experiments!

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- **Wrong**: The linear combination of the three primaries (R, G, B) may produce all of the visible colors.

- This is true only if the centers of the three curves are shifted
  - This means that the wavelengths must change but then we have no longer the same primaries!

- The three curves are not a basis.
Color Fundamentals (cont...)

- The primary colors can be added to produce the secondary colors.
- Mixing the three primaries produces white.
- Mixing a secondary with its opposite primary produces white (e.g. red+cyan).

Important difference:
- Primary colors of light (red, green, blue)
- Primary colors of pigments (colorants)
  - A color that subtracts or absorbs a primary color of light and reflects the other two.
  - These are cyan, magenta and yellow (CMY).
  - A proper combination of pigment primaries produces black.
Distinguishing one color from another:

• **Brightness**: the achromatic notion of intensity.

• **Hue**: the dominant wavelength in a mixture of light waves (the dominant color perceived by an observer, e.g. when we call an object red or orange we refer to its hue).

• **Saturation**: the amount of white light mixed with a hue. Pure colors are fully saturated. Pink (red+white) is less saturated.

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• **Hue and saturation** are called *chromaticity*.

• Therefore, any color is characterized by its brightness and chromaticity.

• The amounts of red, green and blue needed to form a particular color are called *tristimulus* values and are denoted by $X, Y, Z$. 
Color Fundamentals (cont...)

- A color is then specified by its *trichromatic coefficients*:

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

\[x + y + z = 1\]

- For any visible wavelength, the tristimulus values needed to produce that wavelength are obtained by curves compiled by extensive experimentation.

- We will return to that point at the last part of the lecture.

CIE Chromaticity Diagram

- Specifying colors systematically can be achieved using the CIE *chromaticity diagram*.

- On this diagram the \(x\)-axis represents the proportion of red and the \(y\)-axis represents the proportion of green used to produce a specific color.

- The proportion of blue used in a color is calculated as:

\[z = 1 - (x + y)\]
CIE Chromacity Diagram (cont…)

• Point marked “Green”
  – 62% green, 25% red and 13% blue.

• Point marked “Red”
  – 32% green, 67% red and 1% blue.

• The diagram is useful for color mixing.

CIE Chromacity Diagram (cont…)

• Any color located on the boundary of the chromaticity chart is fully saturated (*Pure colors*).

• The point of equal energy (PEE) has equal amounts of red, green and blue.
  – It is the CIE standard for pure white.

CIE Chromacity Diagram (cont…)

- Any straight line joining two points in the diagram defines all the different colors that can be obtained by combining these two colors additively.
- A line drawn from the PEE to any point on the boundary defines all the shades of that particular color.

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• A triangle with vertices at any three fixed pure colors cannot enclose the entire color region.

• The triangle shows the typical color gamut produced by RGB monitors.
• The entire color range cannot be displayed based on any three colors.
• The irregular shape is the gamut achieved by high quality color printers.
CIE Chromacity Diagram (cont…)

- The boundary of the printing gamut is irregular because printing is a combination of additive and subtractive color mixing.
- This is a more difficult process to control than that of displaying colors.

Color Models

- From the previous discussion it should be obvious that there are different ways to model color.
- We will consider two very popular models used in color image processing:
  - RGB (Red Green Blue)
  - HSI (Hue Saturation Intensity)
In the RGB model each color appears in its primary spectral components of red, green and blue.

The model is based on a Cartesian coordinate system.

RGB values are at 3 corners.

Cyan magenta and yellow are at three other corners.

Black is at the origin.

White is the corner furthest from the origin.

Different colors are points on or inside the cube represented by RGB vectors.
Images represented in the RGB color model consist of three component images – one for each primary color.

When fed into a monitor these images are combined to create a composite color image.

The number of bits used to represent each pixel is referred to as the color depth.

A 24-bit image is often referred to as a full-color image as it allows $2^{24} = 16,777,216$ colors.
The HSI Color Model

• RGB is useful for hardware implementations and is serendipitously related to the way in which the human visual system works.
• However, RGB is not a particularly intuitive way in which to describe colors.
• Rather when people describe colors they tend to use hue, saturation and brightness.
• RGB is great for color generation, but HSI is great for color description.

Remainder:

– **Hue**: A color attribute that describes a pure color (pure yellow, orange or red).
– **Saturation**: Gives a measure of how much a pure color is diluted with white light.
– **Intensity**: Brightness is nearly impossible to measure because it is so subjective. Instead we use intensity. Intensity is the same achromatic notion that we have seen in grey level images.
• Intensity can be extracted from RGB images.
• However, human perception of color does not refer to percentages of RGB.
• Remember the diagonal on the RGB color cube that we saw previously ran from black to white.
• Now consider if we stand this cube on the black vertex and position the white vertex directly above it.

---

• The intensity component of any color can be determined by passing a plane perpendicular to the intensity axis and containing the color point.
• The intersection of the plane with the intensity axis gives us the intensity component of the color.
• The saturation of a color (percentage of white missing from the color) increases as a function of distance from the intensity axis.


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• In a similar way we can extract the hue from the RGB color cube.
• Consider a plane defined by the three points cyan, black and white.
• All points contained in this plane must have the same hue (cyan) as black and white cannot contribute hue information to a color.


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• By rotating the shaded plane around the intensity axis we obtain different hues.

• Conclusion:
  – The HSI values can be obtained from the RGB values.
  – We have to work the geometric formulas.

The HSI Color Model

• If we look straight down at the RGB cube as it was arranged previously
  we would see a hexagonal shape with each primary color separated by 120° and secondary colors at 60° from the primaries.

• The HSI model is composed of a vertical intensity axis and the locus of color points that lie on planes perpendicular to that axis.
The HSI Color Model (cont...)

- Hexagonal shape at an arbitrary color point
  - The hue is determined by an angle from a reference point, usually red.
  - The saturation is the distance from the origin to the point.
  - The intensity is determined by how far up the vertical intensity axis this hexagonal plane sits (not apparent from this diagram).

The HSI Color Model (cont...)

- As the only important things are the angle and the length of the saturation vector this plane is also often represented as a circle or a triangle.
Converting From RGB To HSI

• Given a color as R, G, and B its H, S, and I values are calculated as follows:

\[ H = \begin{cases} \theta & \text{if } B \leq G \\ 360 - \theta & \text{if } B > G \end{cases} \]

\[ S = 1 - \frac{3}{(R + G + B)} \left[ \min(R, G, B) \right] \]

\[ \theta = \cos^{-1} \left\{ \frac{1}{2} \left[ (R - G) + (R - B) \right] \right\} \frac{(R - G)^2 + (R - B)(G - B)}{I} \]

\[ I = \frac{1}{3}(R + G + B) \]

Converting From HSI To RGB

• Given a color as H, S, and I it’s R, G, and B values are calculated as follows:

  – RG sector \((0 \leq H < 120^\circ)\)

\[ R = I \left[ 1 + \frac{S \cos H}{\cos (60 - H)} \right], \quad G = 3I - (R + B), \quad B = I(1 - S) \]

  – GB sector \((120^\circ \leq H < 240^\circ)\)

\[ R = I (1 - S), \quad G = I \left[ 1 + \frac{S \cos (H - 120)}{\cos (H - 60)} \right], \quad B = 3I - (R + G) \]
Converting From HSI To RGB (cont…)

- BR sector \((240^\circ \leq H \leq 360^\circ)\)

\[
R = 3I - (G + B), \quad G = I(1 - S), \quad B = I \left[ 1 + \frac{S \cos(H - 240)}{\cos(H - 180)} \right]
\]
Manipulating Images In The HSI Model

- In order to manipulate an image under the HSI model we:
  - First convert it from RGB to HSI
  - Perform our manipulations under HSI
  - Finally convert the image back from HSI to RGB

RGB -> HSI -> RGB

RGB -> HSI -> RGB (cont…)


Hue

Saturation

Intensity

RGB Image

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Pseudocolor Image Processing

• Pseudocolor (also called false color) image processing consists of assigning colors to grey values based on a specific criterion.

• The principle use of pseudocolor image processing is for human visualisation.
  – Humans can discern between thousands of color shades and intensities, compared to only about two dozen or so shades of grey.

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• Intensity slicing and color coding is one of the simplest kinds of pseudocolor image processing.
• First we consider an image as a 3D function mapping spatial coordinates to intensities (that we can consider heights).
• Now consider placing planes at certain levels parallel to the coordinate plane.
• If a value is one side of such a plane it is rendered in one color, and a different color if on the other side.
In general intensity slicing can be summarised as:

- Let \([0, L-1]\) represent the grey scale
- Let \(l_0\) represent black \([f(x, y) = 0]\) and let \(l_{L-1}\) represent white \([f(x, y) = L-1]\)
- Suppose \(P\) planes perpendicular to the intensity axis are defined at levels \(l_1, l_2, ..., l_p\)
- Assuming that \(0 < P < L-1\) then the \(P\) planes partition the grey scale into \(P + 1\) intervals \(V_1, V_2, ..., V_{P+1}\)

Grey level color assignments can then be made according to the relation:

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

where \(c_k\) is the color associated with the \(k^{th}\) intensity level \(V_k\) defined by the partitioning planes at \(l = k - 1\) and \(l = k\).
Pseudocolor Image Processing – Intensity Slicing (cont...)


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Assigning the yellow color to intensity 255 and the blue color to the rest of the intensities may help a human inspector to rapidly evaluate a crack in an image of a weld.

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Pseudocolor Image Processing

Intensity to Color Transformation

- Three independent transformations of the intensity.
- The results are fed into the R, G, B channels.
- The resulting composite image highlights certain image parts.

X-ray images from airport scanning system.
- The image on the right contains plastic explosives.
Pseudocolor Image Processing
Intensity to Color Transformation (cont.)

- Sinusoidal transformation functions.
- Changing the phase or the frequency of the transformation functions can emphasize ranges in the gray scale.
  - A small change in the phase between the transformations assigns a strong color to the pixels with intensities in the valleys.

Pseudocolor Image Processing
Intensity to Color Transformation (cont.)

- Background and explosives are coded with approximately the same color although they differ.
- This is due to the periodicity of the sine waves.
• Explosives and bag content are mapped by similar transformations and were assigned to the same color.
• The observer may “see” through the explosives and not mistake them for the background.

Color Transformations

• Gray scale image transformations may also be applied to each color separately.

Color Transformations (cont.)

- **Intensity adjustment** in RGB, CMYK and HSI spaces.
- The output is the same regardless of the color space.

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Color Transformations (cont.)

- **Color complements.** For enhancement of dark regions.
- Opposite hues in the color circle.
- Straightforward in RGB space.
- No equivalent transformation in HSI space.
  - The saturation (S) component cannot be computed from the S component of the original image (left as an exercise).
Color Transformations (cont.)

- **Color complements.**

![Color complements diagram](image1)

- **Color slicing** for separating objects from their surroundings.
- A first step towards image segmentation.

![Color slicing examples](image2)


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• Tone corrections.

• Correction of color imbalances.
Color Image Smoothing

![Image of color image smoothing](image1)


FIGURE 6.38
(a) RGB Image.
(b) Red component image.
(c) Green component.
(d) Blue component.

Color Image Smoothing (cont…)

![Image of color image smoothing](image2)


FIGURE 6.39
HSI components of the RGB color image in Fig. 6.38(a). (a) Hue. (b) Saturation. (c) Intensity.

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Color Image Smoothing (cont…)

• HSI decouples intensity from color. Suitable for processing only the intensity component of an image.

![Image smoothing](image)

**FIGURE 6.10** Image smoothing with a $5 \times 5$ averaging mask. (a) Result of processing each RGB component image. (b) Result of processing the intensity component of the HSI image and converting to RGB. (c) Difference between the two results.

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Color Image Sharpening

• The difference becomes more pronounced by increasing the filter size.

![Image sharpening](image)

**FIGURE 6.11** Image sharpening with the Laplacian. (a) Result of processing each RGB channel. (b) Result of processing the HSI intensity component and converting to RGB. (c) Difference between the two results.

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Color Image Gradient

- The standard approach of taking the partial derivatives with respect to each color and adding them to form the corresponding gradient image fails.
- The gradient, as we have studied it, refers to a scalar valued 2D function.
- In color images we have a vector valued 2D function.

Color Image Gradient (cont…)

- In both cases (a) and (b), the standard approach would give the same gradient magnitude at the center of the image. However, in (b) we would expect a lower magnitude as only two edges are in the same direction.
The goal is to find a vector pointing in the direction of maximum rate of change of 
\[ \mathbf{c}(x,y) = [R(x,y), G(x,y), B(x,y)]^T \]
(this is the definition of the gradient).

Let \( \mathbf{r} \), \( \mathbf{g} \) and \( \mathbf{b} \) be unit vectors along the R, G and B axes and define:

\[
\mathbf{u} = \frac{\partial R}{\partial x} \mathbf{r} + \frac{\partial G}{\partial x} \mathbf{g} + \frac{\partial B}{\partial x} \mathbf{b}, \quad \mathbf{v} = \frac{\partial R}{\partial y} \mathbf{r} + \frac{\partial G}{\partial y} \mathbf{g} + \frac{\partial B}{\partial y} \mathbf{b}
\]

Let also:

\[
\begin{align*}
g_{xx} &= \mathbf{u} \cdot \mathbf{u} = \mathbf{u}^T \cdot \mathbf{u} = \left| \frac{\partial R}{\partial x} \right|^2 + \left| \frac{\partial G}{\partial x} \right|^2 + \left| \frac{\partial B}{\partial x} \right|^2 \\
g_{yy} &= \mathbf{v} \cdot \mathbf{v} = \mathbf{v}^T \cdot \mathbf{v} = \left| \frac{\partial R}{\partial y} \right|^2 + \left| \frac{\partial G}{\partial y} \right|^2 + \left| \frac{\partial B}{\partial y} \right|^2 \\
g_{xy} &= \mathbf{u} \cdot \mathbf{v} = \mathbf{u}^T \cdot \mathbf{v} = \frac{\partial R}{\partial x} \frac{\partial R}{\partial y} + \frac{\partial G}{\partial x} \frac{\partial G}{\partial y} + \frac{\partial B}{\partial x} \frac{\partial B}{\partial y}
\end{align*}
\]
Color Image Gradient (cont…)

The direction of maximum rate of change of $c(x,y)=[R(x,y), G(x,y), B(x,y)]^T$ is [Di Zenzo 86]:

$$\theta(x, y) = \frac{1}{2} \tan^{-1} \left( \frac{2g_{xy}}{g_{xx} - g_{yy}} \right)$$

and the value of that rate of change is:

$$F_g(x, y) = \left\{ \frac{1}{2} \left[ (g_{xx} + g_{yy}) + (g_{xx} - g_{yy}) \cos(2\theta(x, y)) + 2g_{xy} \sin(2\theta(x, y)) \right] \right\}^{\frac{1}{2}}$$
The noise models discussed for grayscale images are also applicable to color images.

However, in many applications, a color channel may be more or less affected than the other channels.

For instance, using a red color filter in a CCD camera may affect the red component of the image (CCD sensors are noisier at low levels of illumination).

We will take a brief look of how noise carries over when converting from one color model to another.

Noise is less noticeable than it is in a grayscale image.
• The hue and saturation components are significantly degraded. This is due to the nonlinearity of the cos and min operations used in the transformation.

• The intensity component is smoother due to averaging of the three noisy RGB components.

When only one channel is affected by noise, conversion to HSI spreads the noise to all HSI components images.

This is due to the transformation that makes use of all RGB components to compute each HSI component.
Color Perception Model

We have seen at the beginning of the lecture that the human visual system has three primary sensing groups for the cones $S_i(\lambda)$, $i = 1, 2, 3$.

![Diagram showing absorption curves for blue, green, and red wavelengths, with peaks at 445 nm, 535 nm, and 575 nm respectively.]

Color Perception Model (cont...)

The perception of a color with spectral energy distribution $C(\lambda)$ is described by the responses of the three primaries to that color:

$$a_i(C) = \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} S_i(\lambda) C(\lambda) d\lambda, \ i = 1, 2, 3$$

Two colors $C_1(\lambda)$ and $C_2(\lambda)$ are perceived to be identical (they look the same) if:

$$a_i(C_1) = a_i(C_2), \ i = 1, 2, 3$$
Color Perception Model (cont…)

- This means that colors with different spectral distributions, that is
  \[ C_1(\lambda) \neq C_2(\lambda), \]

  may look the same because
  \[ \alpha_1(C_1) = \alpha_2(C_2). \]

- This happens because the human responses to color, \( S_i(\lambda), i=1,2,3, \) are not a basis (they are not orthogonal), and consequently they do not span the space of colors \( C(\lambda). \)

Color Reproduction

- One of the basic problems in the study of color is the reproduction of a color from a set of light sources (primaries).
- Generally, due to the human reception model we consider three primaries.
- Let the three primaries have spectral densities \( P_k(\lambda), k=1,2,3, \) with
  \[
  \int_{\lambda_{\text{min}}(k)}^{\lambda_{\text{max}}(k)} P_k(\lambda) d\lambda = 1, \ k = 1,2,3
  \]
Let also the primaries be linearly independent (no linear combination of any two primaries produces the third primary).

We mix the primaries $P_k(\lambda), k=1,2,3$, with proportions $\beta_k, k=1,2,3$ to reproduce a color with spectrum $C(\lambda)$. This means that $C(\lambda)$ must appear the same to the observer as the linear combination of the primaries:

$$a_i(C) = a_i\left(\sum_{k=1}^{3} \beta_k P_k(\lambda)\right)$$

The problem consists in estimating the mixing proportions $\beta_k, k=1,2,3$:

$$a_i(C) = a_i\left(\sum_{k=1}^{3} \beta_k P_k(\lambda)\right) \Leftrightarrow$$

$$\int_{\lambda_{\text{min}}(i)}^{\lambda_{\text{max}}(i)} S_i(\lambda) C(\lambda) d\lambda = \int_{\lambda_{\text{min}}(i)}^{\lambda_{\text{max}}(i)} S_i(\lambda) \sum_{k=1}^{3} \beta_k P_k(\lambda) d\lambda, \Leftrightarrow$$

$$\int_{\lambda_{\text{min}}(i)}^{\lambda_{\text{max}}(i)} S_i(\lambda) C(\lambda) d\lambda = \sum_{k=1}^{3} \beta_k \int_{\lambda_{\text{min}}(i)}^{\lambda_{\text{max}}(i)} S_i(\lambda) P_k(\lambda) d\lambda, \Leftrightarrow$$
Color Reproduction (cont...)

• Leading to a linear system of 3 equations with $\beta_k$, $k=1,2,3$ as unknowns:

$$\int_{\lambda_{\text{min}}(i)}^{\lambda_{\text{max}}(i)} S_i(\lambda)C(\lambda)d\lambda = \sum_{k=1}^{3} \beta_k \int_{\lambda_{\text{min}}(i)}^{\lambda_{\text{max}}(i)} S_i(\lambda)P_k(\lambda)d\lambda, \Leftrightarrow$$

$$a_i(C) = \sum_{k=1}^{3} \beta_k \left[ a_i(P_k(\lambda)) \right], \ i = 1,2,3.$$

Color Reproduction (cont...)

• In practice, the primary sources are calibrated against a reference white light source with known energy distribution.

• Let $w_k$ denote the amount of the $k$-th primary required to match the reference white. Then, the quantities

$$T_k(C) = \frac{\beta_k}{w_k}, \ k = 1,2,3,$$

• are called tristimulus values of the color $C$.

• The tristimulus values for the reference white are unity.
The tristimulus values of a color give the amount of primaries needed to match that color.

Using the color reproduction equations, we can compute the tristimulus values for each discrete wavelength \( \lambda_0 \), that is, \( C(\lambda) = \delta(\lambda - \lambda_0) \).

Therefore, we can draw the curves for the tristimulus values \( T_k(\lambda) \) for all \( \lambda \).

The negative values for a part of the red curve clearly show that we cannot reproduce every color with the RGB primaries (as we have also explained by the chromaticity diagram).