ME 5405 Machine Vision

Colour Image Processing

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Colour Image Processing

1. Introduction

Colour Image Processing is motivated by two principal factors:

- In automated image analysis, colour is a powerful descriptor that often simplifies object identification and extraction from a scene.

- In image analysis performed by human beings, the motivation for colour is that human beings can discern thousands of colour shades and intensities, compared to about two-dozen shades of gray.

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Colour Image Processing

1. Introduction

Colour image processing is divided into two major areas:

- **Full colour**
  The images in question typically are acquired with a full colour sensor, such as a colour TV camera or colour scanner.

- **Pseudo colour**
  The problem is one of assigning a shade of colour to a particular monochrome intensity or a range of intensities.

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Colour Image Processing

2. Colour Fundamentals

Sir Issac Newton discovered in 1666 that when a beam of sunlight is passed through a glass prism, consists of a continuous spectrum of colours ranging from violet at one end to red at the other. As Plate. I shows, the colour spectrum may be divided into six broad regions: violet, blue, green, yellow, orange, and red. When view in full colour (Plate II), no colour in the spectrum ends abruptly, but rather each colour blends smoothly into the next.

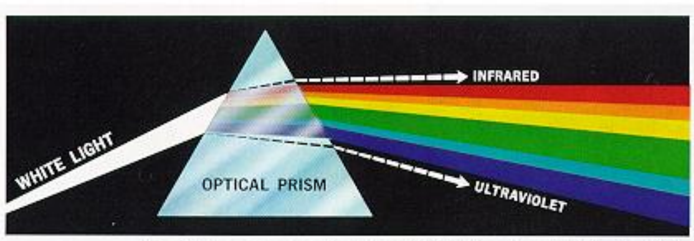

Plate I. Color spectrum seen by passing white light through a prism. (Courtesy of General Electric Co., Lamp Business Division.)

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Colour Image Processing

The colours that human perceives in an object are determined by **the nature of the light reflected from the object.** A body that reflects light that is relatively balanced in all visible wavelengths appears white to the observer. However, a body that favours reflectance in a limited range of the visible spectrum exhibits some shades of colour. For example, green objects reflect light with wavelengths primarily in the 500 to 570 nm range, while absorbing most of the energy at other wavelengths.

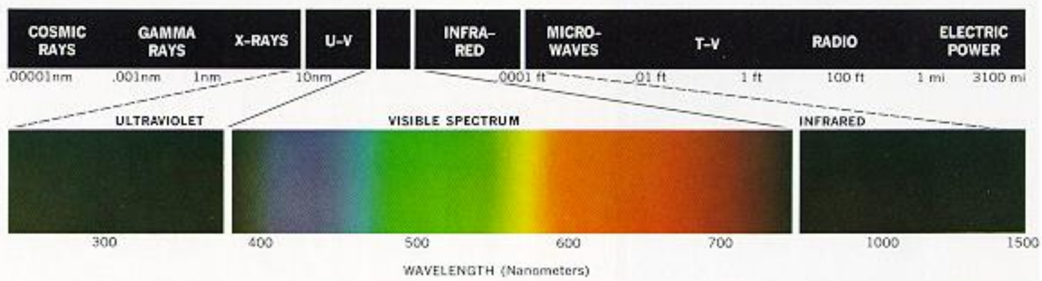

Plate II. A section of the electromagnetic energy spectrum showing the range of wavelengths comprising the visible spectrum. (Courtesy of General Electric Co., Lamp Business Division.)

Colour Image Processing – Colour Fundamentals

2. Colour Fundamentals

Characterisation of light is central to the science of colour.

If the light is achromatic (void of colour), its only attribute is intensity, or amount.

Achromatic light is what viewers see on a black and white TV set, and it has been an implicit component of our discussion of image processing so far.

Thus the term gray level refers to a scalar measure of intensity that ranges from black, to grays, and finally to white.

Colour Image Processing – Colour Fundamentals

2.1 Primary and Secondary Colours

Chromatic light spans the electromagnetic energy spectrum from approximately 400 to 700 nm. Three basic quantities are used to describe the quality of a chromatic light source:

- Radiance is the total amount of energy that flows from the light source, and it is usually measured in watts (W).
- Luminance, measured in lumens (lm), gives a measure of the amount of energy an observer perceives from a light source.
- Brightness, is a subjective descriptor that is practically impossible to measure, it embodies the achromatic notion of intensity and is one of the key factors in describing sensation.

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Colour Image Processing – Primary and Secondary

2.1 Primary and Secondary Colours

Owing to the structure of the human eye, all colours are seen as variable combinations of the so-called *primary colour* red (R), green (G), and Blue(B).

In 1931, for the purpose of standardisation, the CIE (Commission Internationale de l'Eclairage – The International Commission on Illumination), designated the following specific wavelength values to the three primary colours:

Blue = 435.8 nm
Green = 546.1 nm
Red = 700 nm

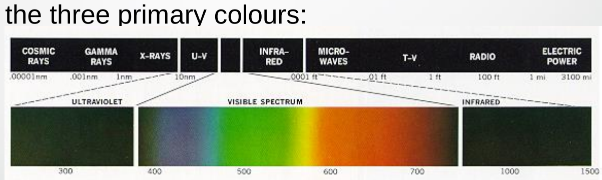

Plate II. A section of the electromagnetic energy spectrum showing the range of wavelengths comprising the visible spectrum. (Courtesy of General Electric Co., Lamp Business Division.)

Note however, that from Plate II, **no single colour may be called red, green or blue.** Thus, it is not true that these three fixed RGB components acting alone can generate all spectrum colours, unless the wavelength is also allowed to vary.

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Colour Image Processing – Primary and Secondary

2.1 Primary and Secondary Colours

The primary colours can be added to produce the *secondary colours* of light –

Magenta	**Red**	**+**	**Blue**
Cyan	**Green**	**+**	**Blue**
Yellow	**Red**	**+**	**Green**

Mixing the three primaries, or a secondary with its opposite primary colour in the right intensities produces white light.

The result is shown in Plate III(a), which also illustrates the three primary colours and their combinations to produce the secondary colours.

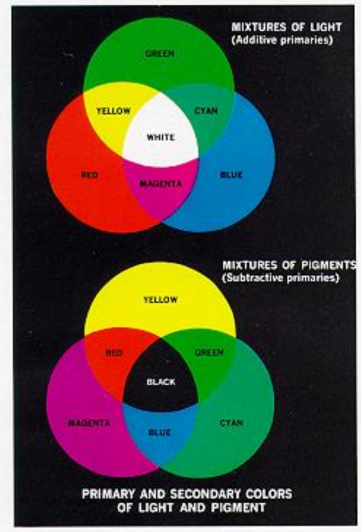

Plate III. Primary and secondary colors of light and pigments. (Courtesy of General Electric Co., Lamp Business Division.)

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Colour Image Processing – Primary and Secondary

It is important to differentiate between the primary colours of light and that of pigments or colorants.

Pigments or Colorant:

A primary colour is defined as one that subtracts or absorbs a primary colours of light and reflects or transmits the other two.

Therefore, the primary colours of pigments are magenta, cyan and yellow, and the secondary colours are red, green and blue.

These colours are shown in Plate III(b). A proper combination of the three pigment primaries, or a secondary with its opposite primary, produces black.

Colour Image Processing – Primary and Secondary

The characteristics generally used to distinguish one colour from another are brightness, hue and saturation.

Brightness embodies the chromatic notion of intensity.

Hue is an attribute associated with the dominant wavelength in a mixture of light waves. Thus hue represents the colour as perceived by an observer; when we call an object red, orange or yellow, we are specifying its hue.

Saturation refers to relative purity or the amount of white light mixed with the hue. The pure spectrum colours are fully saturated. Colours such as pink (red and white) are less saturated, with the degree of saturation being inversely proportional to the amount of white light added.

Hue and saturation taken together are called *chromaticity*, and therefore, a colour may be characterised by its brightness and chromaticity. The amounts of red, green and blue needed to form any particular colour are called the tristimulus values and are denoted, *X, Y,* and *Z*, respectively. A colour is then specified by its trichromatic coefficients, defined as:

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Colour Image Processing – Primary and Secondary

The amounts of red, green and blue needed to form any particular colour are called the tristimulus values and are denoted, *X, Y,* and *Z*, respectively. A colour is then specified by its trichromatic coefficients, defined as:

$$x = \frac{X}{X+Y+Z}$$
$$y = \frac{Y}{X+Y+Z} \qquad (1)$$
$$z = \frac{Z}{X+Y+Z}$$

and obviously,

$$x + y + z = 1 \qquad (2)$$

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Colour Image Processing – Primary and Secondary

For any wavelength of light in the visible spectrum, the tristimulus values needed to produce the colour corresponding to that wavelength can be obtained directly from curves or tables that have been compiled from extensive experimental results from the two following references:

Walsh, J.W.T., Photometry, 1958, Dover, New York, USA.

Kiver,M.S., Color Television Fundamentals, 1965, McGraw-Hill, New York, USA.

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Colour Image Processing – Chromaticity Diagram

2.2 Chromaticity Diagram

Another approach for specifying colours is the *Chromaticity Diagram* (Plate IV), which shows colour composition as a function of ***x* (red) and *y* (green).** For any value of *x* and *y*, the corresponding value of ***z* (blue)** is obtained from equation (2).

For example, the point marked green in Plate IV, has approximately 62% green and 25% red content, and from equation (2), the composition of blue is approximately 13%.

The positions of the various spectrum colours – from violet at 380 nm to red at 780 nm are indicated around the boundary of the tongue shaped chromaticity diagram. These are the pure colours shown in the spectrum of Plate II.

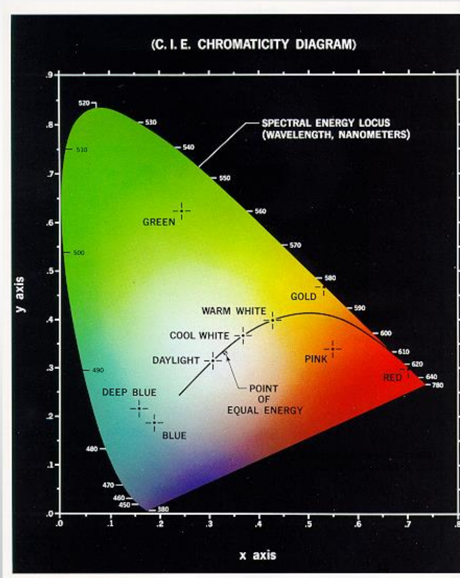

Plate IV. Chromaticity diagram. (Courtesy of General Electric Co., Lamp Business Division.)

Colour Image Processing – Chromaticity Diagram

- Any points not actually on the boundary but within the diagram represents some mixture of spectrum colours.
- The points of equal energy shown in Plate IV correspond to equal fractions of the three primary colours. It represent the CIE standard for white light.
- Any point located on the boundary of the chromaticity diagram is said to be completely saturated. As a point leaves the boundary and approaches the point of equal energy, more white light is added to the colour and it becomes less saturated. The saturation at the point of equal energy is zero.

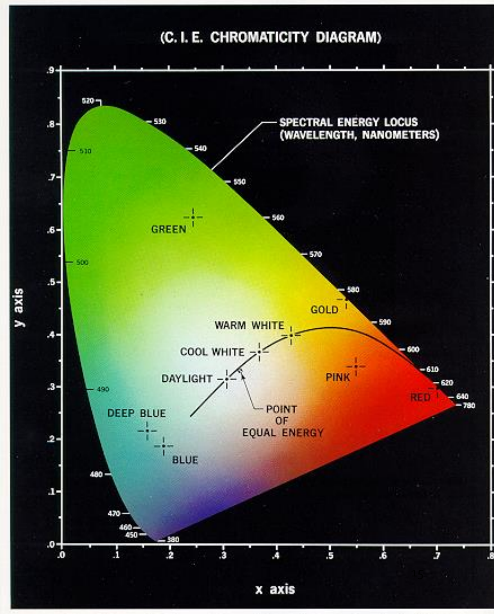

Plate IV. Chromaticity diagram. (Courtesy of General Electric Co., Lamp Business Division.)

Colour Image Processing – Chromaticity Diagram

Usefulness of the Chromaticity Diagram

The diagram is useful for colour mixing, because a straight line segment joining any two points in the diagram defines all the different colour variations that can be obtained by combining these colours additively. Below are two examples:

- Consider a straight line drawn from the red to the green points shown in Plate IV. If there is more red light than green light, the exact point representing the new colour will be on the line segment, but it will be closer to the red point than to the green point.
- Consider a line drawn from the point of equal energy to any point on the boundary of the diagram will define all the shades of that particular spectrum colour.

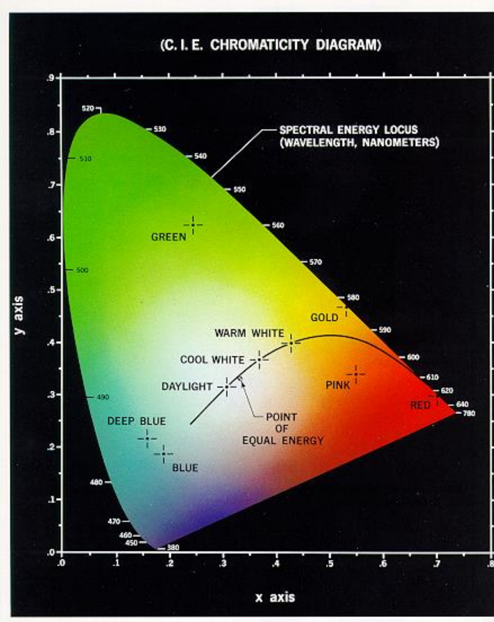

Plate IV. Chromaticity diagram. (Courtesy of General Electric Co., Lamp Business Division.)

Colour Image Processing – Chromaticity Diagram

Extension of this procedure to **three colours** is straightforward.

To determine the range of colours that can be obtained from any three given colours in the chromaticity diagram, we simply draw connecting lines to each of the three colour points. The result is a triangle, and various combinations of the three initial colours can produce any colour inside the triangle.

Note however that a triangle with vertices at any three fixed colour does not enclose the entire colour region in Plate IV. This observation supports graphically the earlier remark that not all colours can be obtained with three single primaries.

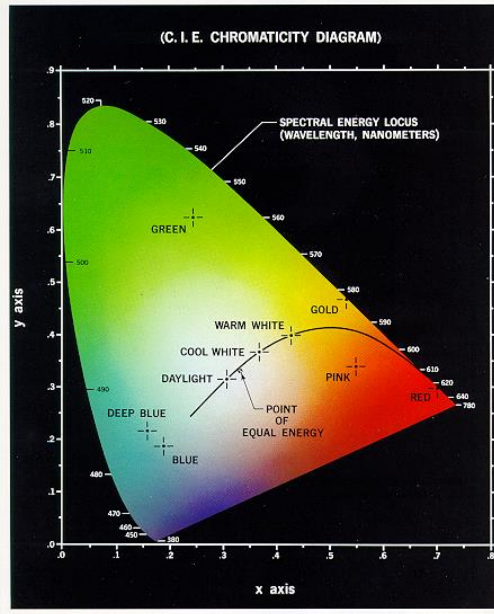

Plate IV. Chromaticity diagram. (Courtesy of General Electric Co., Lamp Business Division.)

Colour Image Processing – Colour Models

3. Colour Models

A colour model is a specification of a 3-D coordinate system and a subspace within that system where each colour is represented by a single point.

Most colour models in use today are oriented toward hardware (such as for colour monitors and printers) or toward applications where colour manipulation is a goal (such as in the creation of colour graphics for animation).

Colour Image Processing – Colour Models

3. Colour Models

The hardware oriented models most commonly used in practice are:

- RGB (red, green, blue) model for colour monitor and broad class of colour video cameras;
- CMY (cyan, magenta, yellow) model for colour printers; and
- YIQ model, which is the standard for colour TV broadcast. In this model, Y corresponds to luminance, and I and Q are two chromatic components called inphase and quadrature, respectively.

Amongst the models frequently used for colour image manipulation are the HSI (hue, saturation, intensity) model and the HSV (hue, saturation, value) model.

The colour models most often used for image processing are the RGB, the YIQ and the HSI models.

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Colour Image Processing – Colour Models

3.1 **The RGB Colour Model**

In the RGB model, each colour appears in its primary spectral components of red, green and blue. This model is based on a Cartesian coordinate system. The colour subspace of interest is in the cube shown in Fig. 1, in which RGB values are at three corners; black is at the origin, and white is at the corner farthest from the origin.

In this model, the gray scale extends from black to white along the line joining these two points, and colours are points on or inside the cube, defined by vectors extending from the origin.

For convenience, the assumption is that all colour values have been normalised so that the cube shown in Fig. 1 is the unit cube, i.e., all values of R, G, and B are assumed to be in the range [0,1].

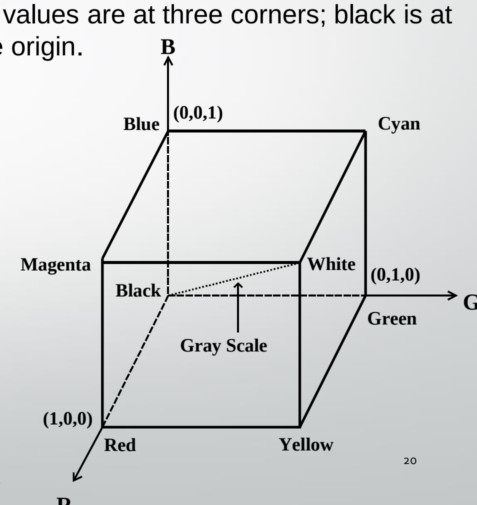

Fig. 1 RGB Colour Cube. Points along the main diagonal have gray values from black at the origin to white at point (1,1,1)

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Colour Image Processing – Colour Models

Images in the RGB colour model consist of three independent image planes, one for each primary colour. Most colour cameras used for acquiring digital images utilise the RGB format, which alone makes this an important model in image processing.

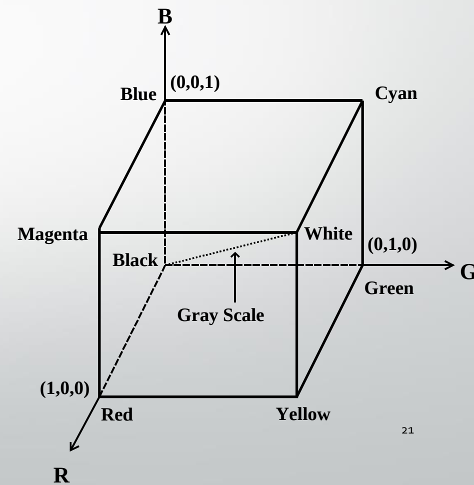

Fig. 1 RGB Colour Cube. Points along the main diagonal have gray values from black at the origin to white at point (1,1,1)

Colour Image Processing – Colour Models

3.2 The CMY Colour Model

Cyan, magenta and yellow are three secondary colours of light, or alternatively, the primary colours of pigments. Thus, cyan subtracts red light from reflected white light, which itself is composed of equal amount of red, green and blue light.

Most devices that deposit colour pigments on paper, such as colour printers and copiers, require CMY data input or perform an RGB to CMY conversion internally. The conversion is performed using the simple operation:

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (3)$$

where again, the assumption is that all colour values have been normalised to the range [0,1].

Colour Image Processing – Colour Models

3.2 The CMY Colour Model

Equation (3) shows that light reflected from a surface coated with pure cyan does not contain red (i.e., $C = 1 - R$); similarly, pure magenta does not reflect green, and pure yellow does not reflect blue.

This equation also shows that RGB values can be obtained easily from a set of CMY values. However, since CMY colour model is used in connection with generating hard copy output, so that the inverse operation from CMY to RGB is generally of no practical interest.

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix} \qquad (3)$$

Colour Image Processing – Colour Models

3.3 The YIQ Colour Model

This model is used in commercial colour TV broadcasting. Basically YIQ is a recording of RGB for transmission efficiency and for maintaining compatibility with monochrome TV standards. In fact, the Y component provides all the video information required by a monochrome television set. The RGB to YIQ conversion is defined as

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.523 & 0.311 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \qquad (4)$$

The YIQ model was designed to take advantage of the human visual system's greater sensitivity to changes to luminance than to changes in hue or saturation. Thus, YIQ standards call for more bandwidth (or bits in the case of digital colour) to be used in representing Y, and less bandwidth in representing I and Q.

Colour Image Processing – Colour Models

- The principal advantages of the YIQ model in image processing is that the luminance (Y) and colour information (I and Q) are decoupled.
- Noting that luminance is proportional to the amount of light perceived by the eye. Thus the importance of this decoupling is that the luminance component of an image can be processed without affecting its colour content.
- We can apply histogram equalisation to a colour image represented in YIQ format simply by applying histogram equalisation to its Y component. The relative colours in the image are not affected by this process.

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Colour Image Processing – Colour Models

3.4 The HSI Colour Model

Recalling that hue is a colour attribute that describes a pure colour (pure yellow, orange or red), whereas saturation gives a measure of the degree to which a pure colour is diluted by white light.

The HSI colour model owes its usefulness to two principal facts.

- The intensity component I, is decoupled from the colour information of the image.
- The hue and saturation components are intimately related to the way in which human beings perceived colour.

These features make the HSI model an ideal tool for developing image processing algorithm based on some of the colour sensing properties of the human visual system.

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Colour Image Processing – Colour Models

Examples of the usefulness of the HSI model range from the design of imaging systems for automatically determining the ripeness of fruits and vegetables, to systems for matching colour samples or inspecting the quality of finished colour goods.

The conversion formulas to go from RGB to HSI and back are considerably more complicated than in the preceding models.

Colour Image Processing – Colour Models

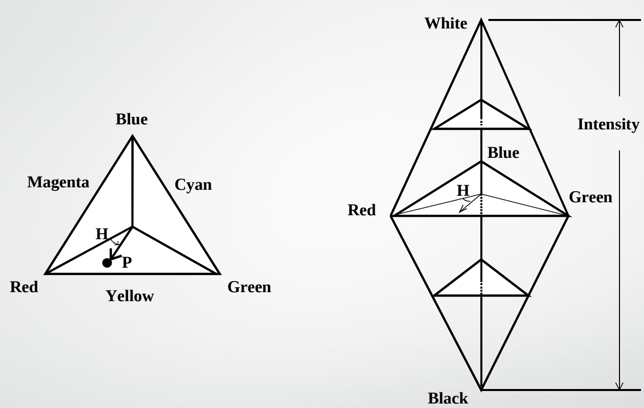
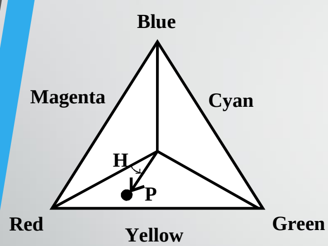
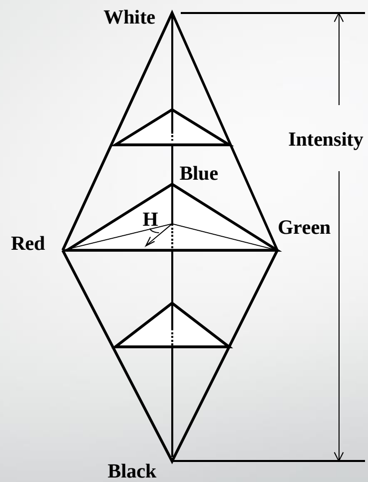


Fig. 2 (a) HSI colour triangle; (b) HSI colour solid.

Fig. 2 shows the HSI colour triangle and colour solid. Combining hue, saturation, and intensity in a 3-D colour space yields the three sided, pyramid like structure shown in Fig.2(b). Any point on the surface of this structure represents a purely saturated colour.

Colour Image Processing – Colour Models





The hue of that colour is determined by its angle with respect to the red axis.

The intensity of that colour is given by the perpendicular distance from the black point (i.e., the greater the distance from black, the greater is the intensity of the colour).

Similar comments apply to points inside the structure, the only difference being that colours become less saturated as they approach the vertical axis.

Colour Image Processing – Colour Models

The expressions for obtaining HSI values in the range [0,1] from a set of RGB values in the same range are:

$$I = \frac{1}{3}(R+G+B) \qquad (5) \qquad\qquad S = 1 - \frac{3}{(R+G+B)}[\min(R,G,B)] \qquad (6)$$

and

$$H = \cos^{-1}\left\{ \frac{\frac{1}{2}\left[(R-G)+(R-B)\right]}{\left[(R-G)^2+(R-B)(G-B)\right]^{1/2}} \right\} \qquad (7)$$

where $H = 360° - H \text{ if } \left(\frac{B}{I}\right) > \left(\frac{G}{I}\right)$

In order to normalise hue to the range [0,1], we let $H = H/360°$.

Finally, when S = 0, it is meaningless to define hue, and similarly, saturation is not defined when I = 0.

Colour Image Processing – Colour Models

For the conversion from HSI to RGB, it is a bit more complicated.
For the RG Sector $(0° < H \leq 120°)$

$$b = \frac{1}{3}(1 - S) \quad (8)$$

$$r = \frac{1}{3}\left[1 + \frac{S \cos H}{\cos(60° - H)}\right] \quad (9)$$

and

$$g = 1 - ((r + b) \quad (10)$$

where

$$r = \frac{R}{R + B + G}$$
$$g = \frac{G}{R + B + G} \quad (11)$$
$$b = \frac{B}{R + B + G}$$

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Colour Image Processing – Colour Models

As $I = \frac{1}{3}(R + G + B)$, the R, G and B components can be obtained as follows:

$$R = 3Ir$$
$$G = 3Ig \quad (12)$$
$$B = 3Ib$$

For the GB sector ($120° < H \leq 240°$)

$$H = H - 120° \quad (13)$$

$$r = \frac{1}{3}(1 - S) \quad (14)$$

$$g = \frac{1}{3}\left[1 + \frac{S \cos H}{\cos(60° - H)}\right] \quad (15)$$

and

$$b = 1 - (r + g) \quad (16)$$

The values of RGB can then be obtained from equation (12).

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Colour Image Processing – Colour Models

For the BR Sector ($240° < H \leq 360°$)

$$H = H - 240° \quad (17)$$

$$g = \frac{1}{3}(1 - S) \quad (18)$$

$$b = \frac{1}{3}\left[1 + \frac{S\cos H}{\cos(60° - H)}\right] \quad (19)$$

$$r = 1 - (g + b) \quad (20)$$

The values of RGB can then be obtained from equation (12).

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Colour Image Processing – Full Colour Image Processing

4, Full Colour Image Processing

We shall present some details the role of full colour techniques for image enhancement. We are interested in the HSI model for the two reasons:

(1) the intensity and colour information in this model are decoupled; and

(2) the hue and saturation are closely related to the way in which human beings describe colour perception.

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Colour Image Processing – Full Colour Image Processing

4.1 HSI component images from an RGB image

This example serves to deepen our understanding of the HSI model itself. Note that an image processed in HSI space must be converted back to RGB for display.

Plate V(a) shows an RGB test pattern consisting, at the top, of eight thin bands that contain black, followed by the pure primaries and secondaries (the order shown has no particular significance), and finally ending in white.

These eight bands are followed by a broad multi-colour band that ranges across from blue, to green, to red. This band is followed by two gray-scale wedges in opposite directions. The colour patterns then repeat themselves going the other way to form a square image.

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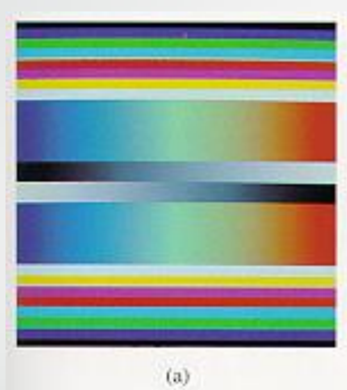
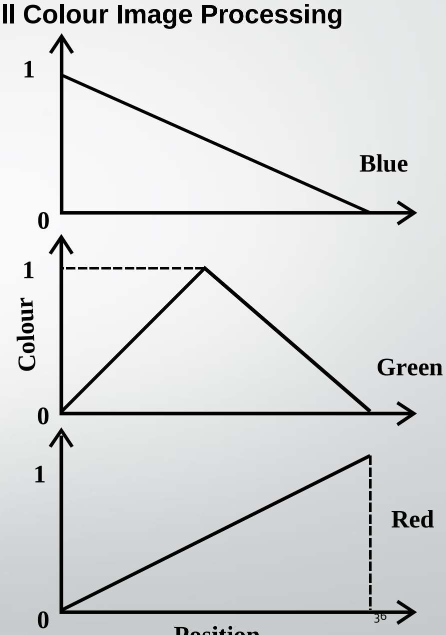
Colour Image Processing – Full Colour Image Processing

Fig. 3 shows the mixture of red, green and blue used to produced the band of varying colour in Plate V(a). Note that pure blue is achieved on the extreme left, pure red on the extreme right and equal parts of red and blue with twice the amount of green give the colour at the centre of the band.





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Colour Image Processing – Full Colour Image Processing

For the colour images shown in Plate V(a), 8-bits per colour component were used. Thus each pixel in a component image has values in the range [0,255]. In our assumption of each colour component values vary in the range [0,1], we can take it as the value varies between 0 and 1 in increments of 1/255.

The situation with HSI is slightly different. Each pixel in the hue image has values expressed in degrees. With 8 bits, 256 such values can be represented in the range [0°, 360°] in increment of $n(360/255)$ for $n = 0, 1, 2, \ldots, 255$. Similarly, pixel in the saturation image may be viewed as having values from 0 (no saturation) to 1 (full saturation) in increments of 1/255.

(a)

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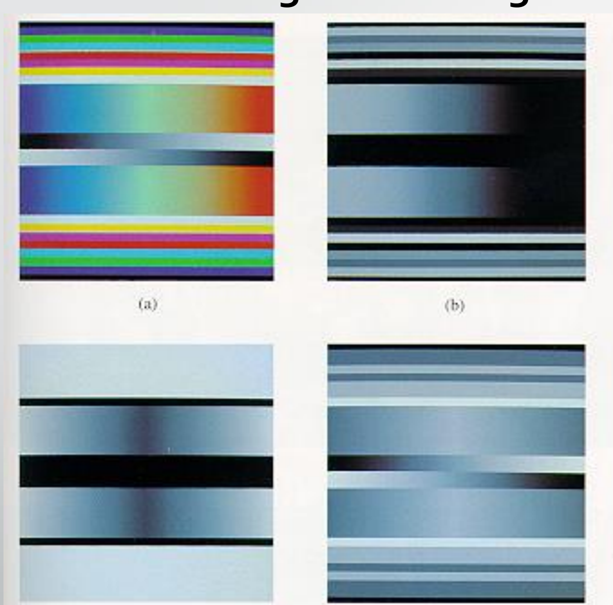
Colour Image Processing – Full Colour Image Processing



(a) (b) (c) (d)

Plate V (a) Original RGB image, (b)-(d) Hue, Saturation, and intensity image.

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Colour Image Processing – Full Colour Image Processing

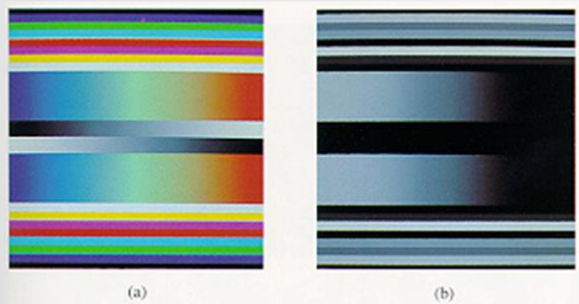
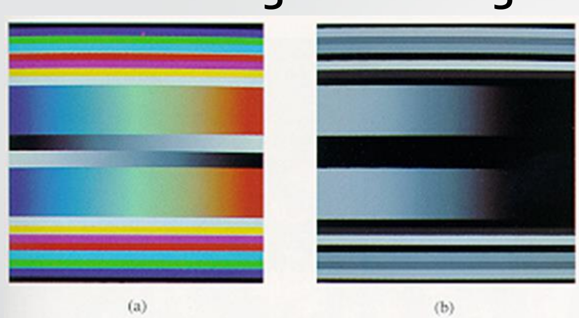


Plate V(b), which shows the hue image obtained from the RGB image in Plate V(a) by using equation (7). As the monochrome component shown in the RGB image has zero saturation, hue is not defined (see discussion after Equation (7)) for those region; they are arbitrary shown in black in Plate V(b).

With hue values in degrees, the grays in Plate V(b) must be interpreted as angles (measured from red, according to Fig. 2). Thus, lighter shades of grays in Plate V(b) correspond to increasing larger angle values. Because reds have the smallest angle values (See Fig. 2), we expect that the reds in Plate V(a) will appear as the darkest grays in Plate V(b), that yellow will appear the next lighter shade of gray, and so on. for green, cyan, blue, and magenta, in that order. This result, in fact is the case as we can see by comparing the colours in Plate V(a) with the grays in Plate V(b). Note in particular the variations in gray corresponding to the varying colour bands.

Colour Image Processing – Full Colour Image Processing



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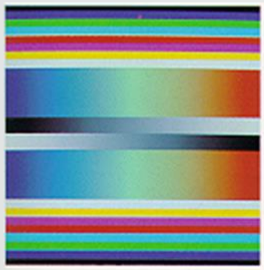
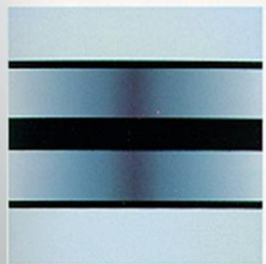
- Note in particular the variations in gray corresponding to the varying colour bands.

Colour Image Processing – Full Colour Image Processing



(a)



(c)

- Plate V(c) shows the saturation image obtained from the RGB image using equation (6). The maximally saturated pure primary and secondary colours appear as white (maximum) in the saturation image. As saturation is not defined when the intensity I is zero (see the discussion following equation (7)), all black components of the RGB image are shown arbitrarily in white in Plate V(c). Note that whites in Plate V(a) appear as black in Plate V(c), because white corresponds to zero saturation.

- The grays corresponding to the varying colour band are lighter towards both ends of the band, indicating greater colour saturation there. The grays correspond to the centre (green) portion of the band are darker than in the extreme portions of the band indicating less saturation in the green region. This condition is consistent with the way in which the dominant green part of the test pattern was generated (See Fig. 3).

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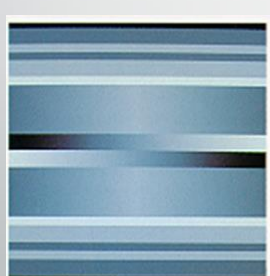
(a)



(d)

- Plate V(d) shows the intensity component of the HSI image obtained using equation (5). As expected, black, white and grays appear as in the RGB image.
- The component corresponding to the pure primary colours all have the same value and thus appear in constant gray in Plate V(d).
- The pure secondary colours also yield constant values of intensity, but they are double the value of the intensity corresponding to the primaries and thus appear a lighter gray. This result is also expected, because a secondary of light is obtained by adding two primaries.
- The intensities corresponding to the varying colour band also are as expected, and vary from dark, to bright, and back to dark.

Colour Image Processing – Full Colour Image Processing

4.2 Enhancement using the HSI model

Plate VI (a) Original RGB image. (b) Result of histogram equalisation.

As we have indicated previously, the HSI model is ideally suited for image enhancement, because the intensity component is decoupled from the colour information in an image. Therefore any monochrome enhancement technique discussed in the chapter on Image Enhancement can be carried over as a tool for enhancing full colour images. It simply calls for converting the image to the HSI format, processing the intensity component, and converting the result to RGB for display. The colour content of the image is not affected. Plate VI illustrates this approach.

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4.2 Enhancement using the HSI model

Plate VI (a) Original RGB image. (b) Result of histogram equalisation.

Due to the fact that histogram equalisation has a tendency to brighten images significantly, the colour components appear somewhat different than in the original image. Although the hue and saturation are the same, the colours appear lighter because of the increase in intensity. Applying this enhancement technique to each component of the RGB image would increase visible detail and brightness, but the resulting colours would have nonsensical hues as a result of changes of relative values between corresponding pixels in the three RGB component images.

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