CHAPTER II

COLOR IMAGE THEORIES

Some of color image theories that are related and applied to this research will be described briefly in this chapter as follows.

Light and Color

Light is a spectrum of electromagnetic energy that can be detected by human eyes. This visible spectrum is only a very narrow band lying within the entire electromagnetic spectrum and its wavelengths range from 380 to 750 nanometers (nm) as illustrated in Fig. 2.1.[1] In the visible spectrum, there are three primary hues* or colors: red, green, and blue. The wavelength of the red hue is about 630 nm, the green hue approximately between 480 and 560 nm, and the blue hue around 480 nm[2]

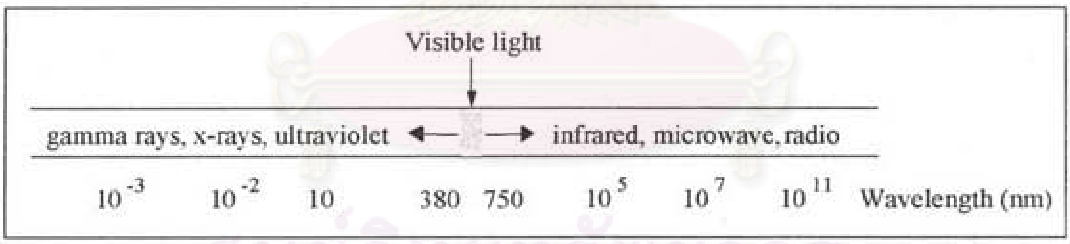

Fig. 2.1 The visible spectrum of electromagnetic spectrum

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[1] Francis S. Hill, Jr., Computer Graphics (New York: Macmillan, 1990), p. 564.

* Hue is the quality of color which is described by the words such as red, green, blue, cyan, magenta, yellow, etc.

[2] Fred W. Billmeyer, Jr. and Max Saltzman, Principles of Color Technology, 2nd ed. (New York: John Wiley & Sons, 1981), p. 4.

The limitation of such narrow band of the visible spectrum is due to the relative insensitivity of human visual system which is essential to describe before any further color image theories can be developed.

1. The Human Visual System

The visual system of human consists of the eyes, the nervous system, and the brain. The eye is approximately a sphere with an average diameter of about 2 cm. A horizontal cross section of an eye is illustrated in Fig. 2.2.[3] The eye ball is formed by three major layers: the *sclera*, the *choroid*, and the *retina*.

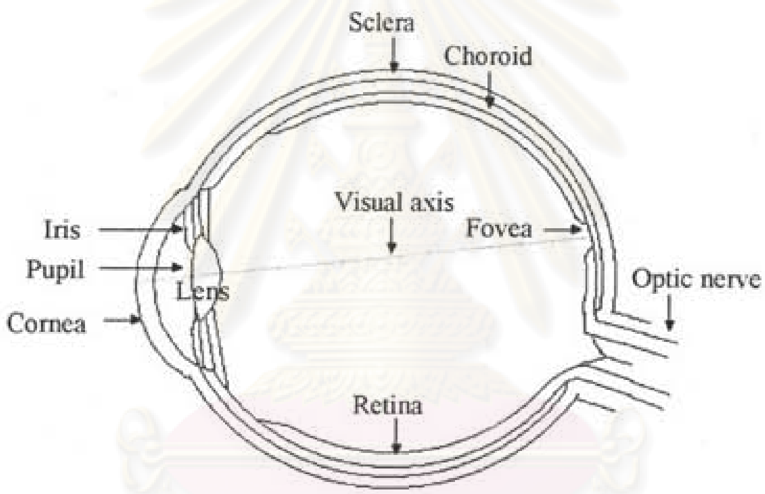

Fig. 2.2 A simplified cross section diagram of a human eye

1.1 The Sclera

The Sclera comprises the white outer cover of the eye and the *cornea*, a tough and transparent membrane. The main function of the cornea is to refract light, similar to a lens of a camera.

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[3] Rafael C. Gonzalez and Richard E. Woods, Digital Image Processing. (Massachusetts: Addison-Wesley, 1992), p. 22.

1.2 The Choroid

The Choroid is a thin membrane lying under the sclera. It contains a network of blood vessels, and *pigment cells* that help absorbing light entering the eye to prevent it from being transmitted beyond the eye globe. At its front extreme is the *iris* which acts like the diaphragm of a camera. The central hole of the iris is the *pupil* of which the size can be changed to control the amount of light entering the eye. The diameter of the pupil varies from around 2 mm to 8 mm.

1.3. The Retina

The Retina is the innermost membrane where the entering light is focused by the lens. The light is then converted to natural signal by the *photoreceptor cells* and then transmitted by the optic nerve to the brain. There are two kinds of receptors,*rods* and *cones*:

1.3.1 Rods

Rods are very sensitive to light. Only a small amount of light is needed to activate this type of cells. Thus, they are primarily used for dim-light (*scotopic*) vision. The number of rods in each eye is about 75 to 150 million cells.

1.3.2 Cones

Cones are less sensitive to light than rods, but responsible for perceiving colors. Thus, they are primarily for bright-light (*photopic*) vision. The number of cones in each eye is approximately six to seven million cells. Most of them reside in the central portion of retina, called the*fovea* which is the best area for color perception of the eye.

According to the *tristimulus theory*, there are three types of cones, each of which is most stimulated by red, green, and blue light respectively. These cones send natural signals of red, green, and blue via the nervous system to the brain where the signals are combined and interpreted as colors. This phenomenon forms the *additive color system* which will be described in the next section.

2. Additive Color System

Since humans only sense the tristimulus values of red, green, and blue, these three colors are called *primary colors*. Colors are produced by adding together the primary color lights as illustrated in Fig. 2.3, and the resulting colors are called *additive colors*.[4] Such is the situation with the color Cathode Ray Tube (CRT) which consists of three electron guns representing the three additive primary colors, and a screen with triads of red, green, and blue phosphor dots. The three electron guns produce electron beams to excite these phosphors, and each triad then forms a local color.[5]

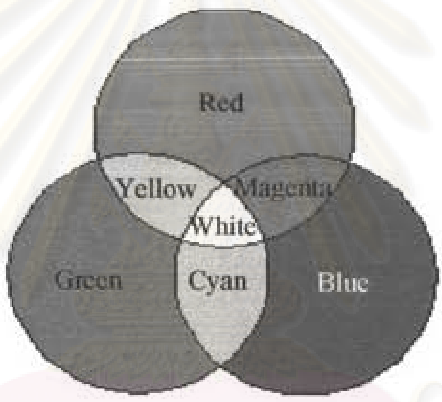

Fig. 2.3 Primary colors of the additive color system

According to experiments conducted by Commission Internationale de l' Éclairage (CIE), humans do not perceive all wavelengths within the visible spectrum equally. The result of these experiments yielded the curve known as *CIE Standard Observer curve*,[6] as illustrated in Fig. 2.4. The curve shows that human eyes are rather

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[4] Edward Angel, Computer Graphics (Massachusetts: Addison-Wesley, 1990), pp. 286-287.

[5] Bruce A. Artwick, Microcomputer Displays, Graphics, and Animation, (New Jersey: Prentice-Hall, 1984), p. 71.

[6] Edward Angel, Computer Graphics, pp. 282-290.

imperfect filters of the electromagnetic spectrum. Near to the extremes of visual spectrum, human eyes have greatly decreased sensitivity, since the peak blue response is around 440 nm; that for green is about 545 nm; and that for red is about 580 nm. It is also suggested from the curve that the eye's response to blue light is much less strong than is its response to red and green.[7]

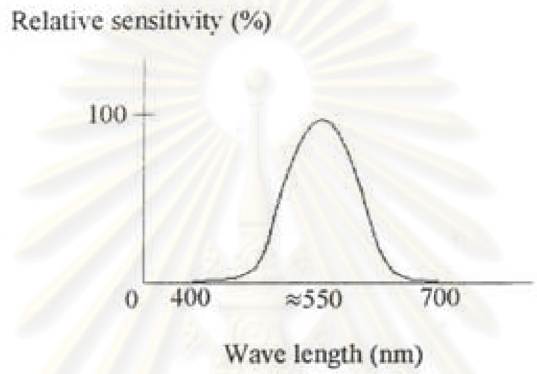

Fig 2.4 CIE Standard Observer curve

Color Models

A color model is a specification for explaining the properties or behavior of color within a particular context. Though the combinations of red, green, and blue (RGB) are best represented on a color monitor. Several other color models are also useful, especially for providing more intuitive color notions[8]

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[7] James D. Foley et al., Computer Graphics Principles and Practice, 2nd ed. (Massachusetts: Addison-Wesley, 1990), pp. 576.-577.

[8] Donald Hearn and M. Pauline Baker, Computer Graphics (London: Prentice-Hall, 1986), p. 299.

1. The RGB Color Model

The RGB (red, green, and blue) color model is the model applied to color CRT monitors exploiting the Cartesian coordinate system. This model is the unit cube as illustrated in Fig. 2.5.[9] The colors on the main diagonal (dotted line) are gray levels.

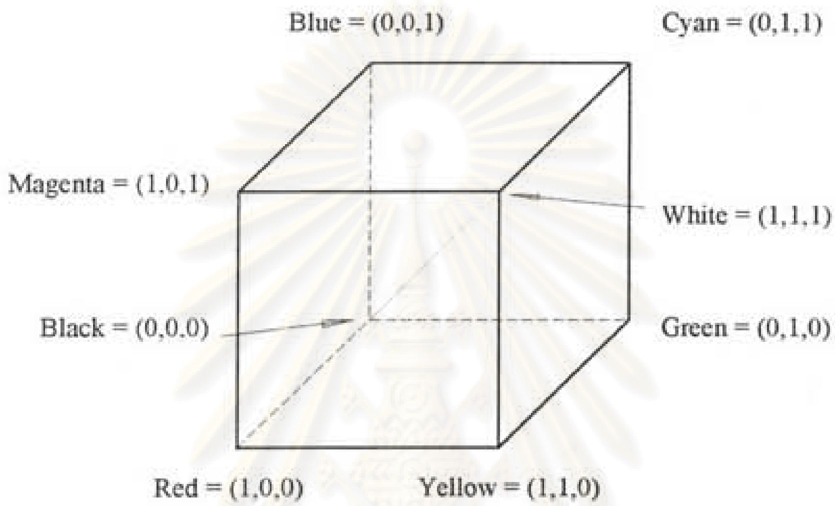

Fig. 2.5 The RGB color model

2. The HSV and HLS Color Models

The HSV (hue, saturation, value) model (also called the HSB model, with B for brightness) and HLS model (with L for lightness) are user-oriented models based upon the intuitive notions of colors. The HSV model is a hexcone, or six-sided pyramid, and the HLS model is a double hexcone, as illustrated in Fig. 2.6(a) and Fig. 2.6(b).[10] respectively. The value of H refers to a pure color and is measured by the angle around the vertical axis, with red at 0° (or 360°), green at 120°, and so on. The black, gray levels, and white colors are on the vertical axis (see Fig. 2.6(a) and Fig. 2.6(b)). The value of S refers to how intense or pale the color is and is ranged from 0 on the vertical axis

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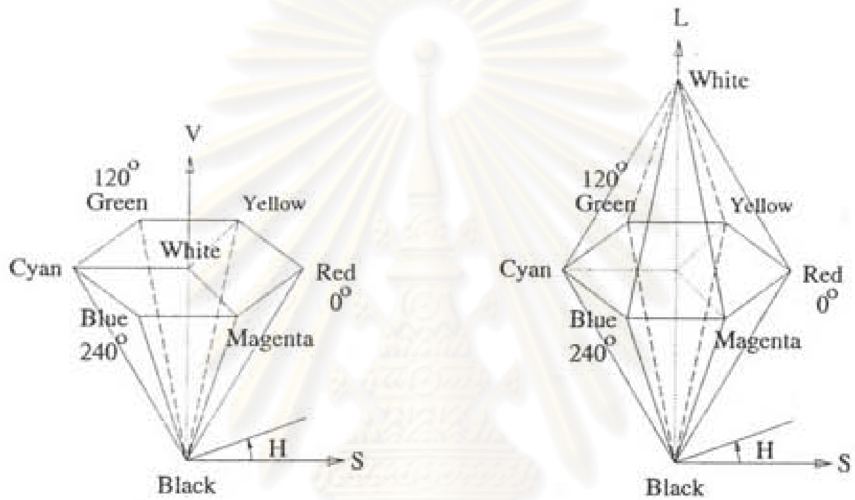
[9] James D. Foley et al., Computer Graphics Principles and Practice, 2nd ed., p. 585.

[10] Ibid., pp. 590-594.

to 1 on the triangular sides of hexcone. Both H and S are the same in HSV and HLS models. The V (value, or B (brightness)) and L (lightness) values are ranged from 0 to 1 but inapplicable in human sense as different colors with the same V and L values are not of the same perceived brightness. RGB and HSV can be converted back and forth using the relation that the top of the HSV hexcone is the projection of the RGB cube along the diagonal from white toward black as shown in Fig. 2.7 and by Algorithm 2.1 and 2.2.[11]



(a) The HSV color model (b) The HLS color model

Fig. 2.6 The HSV and HLS color models

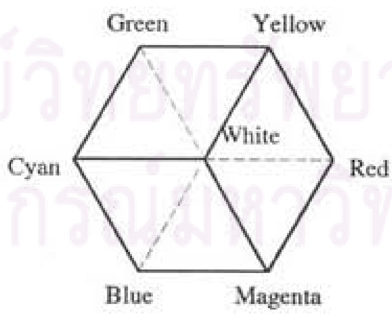


Fig. 2.7 RGB cube viewed along the main diagonal

[11] Steven Harrington, Computer Graphics A Programming Approach, 2nd ed. (New York: McGraw-Hill, 1987), pp. 385-387.

Algorithm 2.1 RGB-to-HSV (R, G, B, H, S, V) Converts from red, green, and blue values in the range 0 to 1 to hue, saturation, and value

Hue is expressed in degrees from 0 to 360

Saturation and value range from 0 to 1

Arguments	R, G, B	:	the red, green, and blue coordinates
	H, S, V	:	returning values of the hue, saturation, and value
	R1, G1, B1	:	representing how relatively close the color is to red, green, and blue
	X	:	intensity of the minimum primary color
	H1	:	the hue in units of 1 to 6

```
BEGIN
   H1 ← 0;
   find dominant primary color
   V ← MAX(R, G, B);
   find the amount of white
   X ← MIN(R, G, B);
   determine the normalized saturation
   S ← (V - X) / V;
   IF S=0 THEN RETURN;
   R1 := (V - R) / (V - X);
   G1 := (V - G) / (V - X);
   B1 := (V - B) / (V - X);
   in which section of the hexagon does the color lie?
   IF R = V THEN
       IF G = X THEN H1 ← 5 + B1
       ELSE H1 ← 1 - G1
   ELSE IF G = V THEN
```

IF B = X THEN H1 ← R1 + 1

ELSE H1 ← 3 - B1

ELSE

IF R = X THEN H1 ← 3 + G1

ELSE H1 ← 5 - R1;

convert to degrees

H ← H1 × 60

RETURN;

END;

As an example, the RGB coordinates (0.7, 0.1, 0.4) can be converted to the equivalent HSV coordinates as follows.

$$V = MAX(0.7, 0.1, 0.4) = \underline{0.7}$$

$$X = MIN(0.7, 0.1, 0.4) = 0.1$$

$$S = (V - X) / V = \frac{0.7 - 0.1}{0.7} = \underline{0.86}$$

$$R1 = (V - R) / (V - X) = \frac{0.7 - 0.7}{0.7 - 0.1} = 0$$

$$G1 = (V - G) / (V - X) = \frac{0.7 - 0.1}{0.7 - 0.1} = 1$$

$$B1 = (V - B) / (V - X) = \frac{0.7 - 0.4}{0.7 - 0.1} = 0.5$$

R=V, G=X; $H1 = 5 + B1 = 5.5$

$$H = H1 \times 60 = 5.5 \times 60 = \underline{330}$$

Thus, HSV = (330, 0.86, 0.7)

Algorithm 2.2 HSV-TO-RGB (H, S, V, R, G, B) Converts hue, saturation, and value coordinates to red, green, and blue

Arguments H, S, V : the hue, saturation, and value

R, G, B : for return values of the red, green, and blue coordinates

Local H1 : the hue in units of 1 to 6

I	:	integer part of the H1 hue, indicates the dominant color
F	:	fractional part of the H1 hue, used to determine second color
A	:	an array that holds the three color values while deciding which is which

```
BEGIN
    convert from degrees to hexagon section
    H1 ← H / 60;
    find the dominant color
    I ← INT(H1);
    F ← H1 - I;
    A[1] ← V;
    A[2] ← V;
    A[3] ← V × (1 - (S × F));
    A[4] ← V × (1 - S);
    A[5] ← A[4];
    A[6] ← V × (1 - (S × (1 - F)));
    map strengths to RGB
    IF I > 4 THEN I ← I - 4 ELSE I ← I + 2;
    R ← A[I];
    IF I > 4 THEN I ← I - 4 ELSE I ← I + 2;
    B ← A[I];
    IF I > 4 THEN I ← I - 4 ELSE I ← I + 2;
    G ← A[I];
    RETURN;
END;
```

As an example, the HSV coordinates (220, 0.67, 0.9) can be converted to the equivalent RGB coordinates as follows.

$H1 = H / 60 = \frac{220}{60} = 3.67$

$I = INT(H1) = 3$

$F = H1 - I = 3.67 - 3 = 0.67$

$A[1] = V = 0.9$

$A[2] = V = 0.9$

$A[3] = V \times (1 - (S \times F)) = 0.9 \times (1 - (0.67 \times 0.67)) = 0.5$

$A[4] = V \times (1 - S) = 0.9 \times (1 - 0.67) = 0.3$

$A[5] = A[4] = 0.3$

$A[6] = V \times (1 - (S \times (1 - F))) = 0.9 \times (1 - (0.67 \times (1 - 0.67))) = 0.7$

I=3; $I = I + 2 = 3 + 2 = 5$

$R = A[I] = A[5] = \underline{0.3}$

I=5; $I = I - 4 = 5 - 4 = 1$

$B = A[I] = A[1] = \underline{0.9}$

I=1; $I = I + 2 = 1 + 2 = 3$

$G = A[I] = A[3] = \underline{0.5}$

Thus, RGB = (0.3, 0.5, 0.9)

3. The YIQ Color Model

The YIQ [12] (*luminosity*, *inphase*, and *quadrature*) color model is developed by the National Television System Committee (NTSC) and used in color television broadcasting. The Y value represents perceived brightness, or luminosity. I and Q are chrominance components of color television signals transferred in two phase angles,

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[12] Steven Harrington, Computer Graphics A Programming Approach, 2nd ed., p. 376.

inphase and quadrature-phase, which are different by 90°. Y can be calculated by the following equation[13]

$$Y = 0.299 \times R + 0.587 \times G + 0.114 \times B \qquad (2.1)$$

Color Image Processing

This section describes the color image processing algorithms employed in this research.

1. Image Inversion

The *image inversion* algorithm exploits the *subtractive color system* in which *complementary color* of a color can be specified by subtracting that color from white light. In other words, the complementary color pairs are two colors that can be combined or added to produce white light. Complementary colors are also called *inverse colors* or *negative colors*. As cyan (C), magenta (M), and yellow (Y) are the complements of red, green, and blue, respectively, they are called *subtractive primary colors*. This coordinate system of (C, M, Y) forms another color model called the *CMY color model*. A diagram of the CMY color model is illustrated in Fig. 2.8.

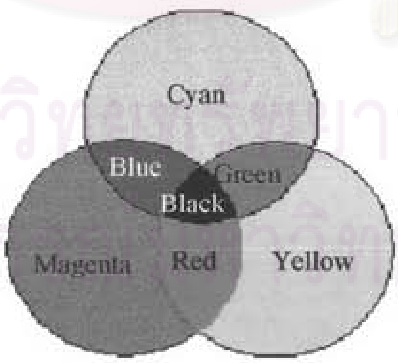

Fig. 2.8 The CMY color model

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[13] James D. Foley et al., Computer Graphics Principles and Practice, 2nd ed., p. 589.

As CMY is the complement of RGB and can be produced by subtracting from white light which all the RGB values are 1's, the relation can be represented by the following equation:[14]

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (2.2)$$

For the above reason, an *inverse image* (or a *negative image*) can be produced by converting the RGB values of every pixel on the image to its complements, CMY values.

It is noted that the inverse image of an image already inverted is the original *positive image*, since:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} C \\ M \\ Y \end{bmatrix} \quad (2.3)$$

2. Color to Gray Level Conversion

The *color to gray level conversion* algorithm is for producing the perceived brightness representation called the gray scale image of an image, as if it is displayed on a black-and-white monitor. By exploiting the YIQ color model, a gray scale image can be obtained by converting all the RGB values of each pixel on the color image to its Y value using Equation (2.2).

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[14] James D. Foley et al., Computer Graphics Principles and Practice, 2nd ed., p. 588.

3. Color Image Enhancement

The color image enhancement methods applied to this research were modified from some of those of the gray scale images. The two essential methods for adjusting exposure* of color images in the RGB color model are presented here:

3.1 Brightness Modification

Brightness is a measure of overall intensity of an image. The lower the brightness is, the closer to black the image will be; the lighter the brightness is, the closer to white the image will be.

For a gray scale image, *brightness modification* is approached by adding or subtracting the gray level of every pixel on the image by a constant value. When such operation yields an out-of-range value, the resulting gray level is trimmed and the extreme value is used instead. For example, to increase the brightness of a gray scale image by 30%, the gray levels of the pixels on the image will be increased by 30%, except that the gray level of 70% and up will be converted to 100%, as illustrated in Fig. 2.9.

Extending to color images, each of RGB values is to be processed separately by the above algorithm. For example, after decreasing brightness by 40%, a pixel for the RGB coordinates (0.8, 0.2, 0.5) will become (0.4, 0, 0.1).

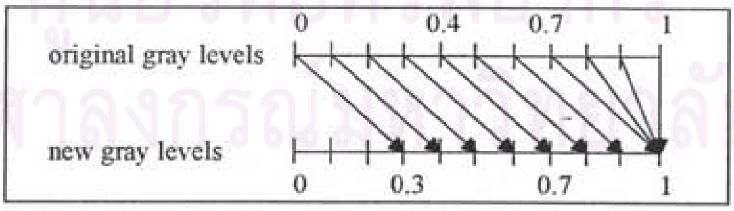

Fig. 2.9 Increasing brightness by 30%

* Exposure is brightness and contrast setting of an image.

3.2 Contrast Modification

Contrast is the spread of gray levels in an image.[15] A low-contrast image has a small range of gray levels. On the other hand, a high-contrast image has a large range of gray levels.

Two most commonly used approaches to *contrast modification* are *histogram modification*[*] approach and filtering approach. There are many contrast enhancement techniques employing histogram modification, e.g., *thresholding*, *bunching* or *quantizing*, *splitting* or *local contrast enhancement* and *histogram equalization*.[16] The examples of filtering techniques are *lowpass filtering*, *highpass filtering*, and *homomorphic filtering*.[17] The histogram modification technique used to achieve contrast modification in the BW2COLOR software is histogram splitting which is described here.

According to the histogram modification algorithm exploited in the BW2COLOR software, the contrast of a gray scale image can be modified by stretching or compressing the gray band. To increase the contrast, the gray band must be stretched. On the other hand, to decrease the contrast, the gray band must be compressed. In the case of contrast stretching, the out-of-range values are assigned to the extreme values. Finally, the resulting band is then used instead of the original band.

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[15] Adrian Low, Introductory Computer Vision and Image Processing (London: McGraw-Hill, 1991), pp. 52 - 56.

[*] Histogram modification is an image enhancement technique. It is done by changing the distribution of the pixel values across the full range of brightness levels. This technique often improves image details, especially when the original data distribution range is narrow.

[16] Adrian Low, Introductory Computer Vision and Image Processing pp. 52-56.

[17] Rafael C. Gonzalez and Richard E. Woods, Digital Image Processing, pp. 213-218.

For instance, to increase the contrast of a gray scale image by 60%, the band will be stretched so that the original gray levels 0.3 (=0+$\frac{0.6}{2}$) and 0.7 (=1-$\frac{0.6}{2}$) will be converted respectively to the black (0) and the white (1) extremes on the resulting band, as illustrated in Fig. 2.10. The gray levels between the two extremes can be calculated by *linear interpolation*.

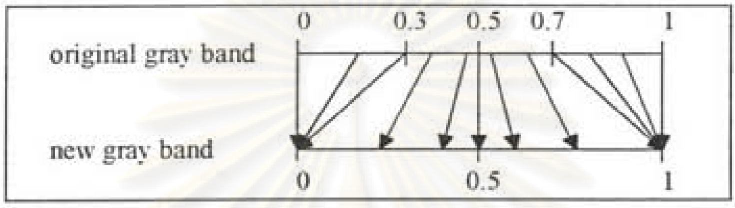

Fig. 2.10 Increasing contrast by 60%

To decrease the contrast of a gray scale image by 40%, the band will be compressed so that the extreme gray levels 0 and 1 will be converted respectively to the gray levels 0.2 and 0.8 on the resulting band, as illustrated in Fig. 2.11.

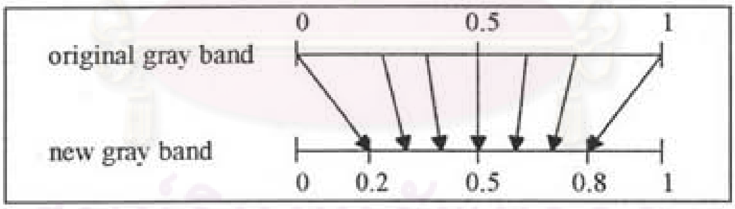

Fig. 2.11 Decreasing contrast by 40%

By applying the same idea to color images, each of the RGB values will be processed separately by using the algorithm above. For example, after increasing contrast by 20%, a pixel of RGB coordinates (0.8, 0, 0.2) will become (0.85, 0, 0.15) as illustrated in Fig. 2.12.

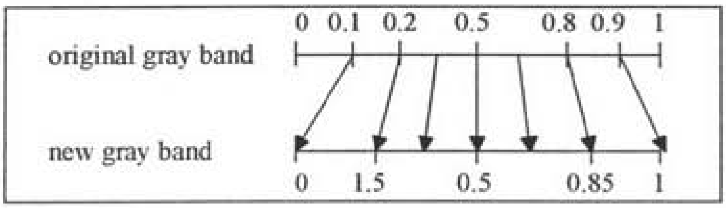

Fig. 2.12 Increasing contrast by 20%

4. Coloring Gray Scale Images

Assigning colors to a gray scale image can improve appearance to human viewers for two reasons. Firstly, human eye is more capable of discriminating colors than gray levels.[18] In other words, the number of distinguishable gray levels is much smaller than the number of distinguishable colors.[19] Secondly, color images are usually much more attractive than gray scale ones.

There are two classes of coloring depending on the purposes: real coloring and *false coloring* or *pseudo coloring*.

4.1 Real Coloring

Real Coloring is the method of assigning natural colors to a gray scale photographic image to make it look natural. To do this, a sophisticated image processing and high degree of human interposition are required. For instance, a software may need the help from users to assign hues to some gray levels before it can automatically calculate the proper colors for the remaining gray levels.

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[18] Lisa G. Thorell and Wanda J. Smith, Using Computer Color Effectively (New Jersey: Prentice-Hall, 1990), pp. 203 - 207.

[19] Jae S. Lim, Two-Dimensional Signal and Image Processing (New Jersey: Prentice-Hall, 1990), pp. 511 - 512.

4.2 False Coloring and Pseudo Coloring[20]

There are two denominations for this class of coloring depending on the type of gray scale image. In the case that the image is colored in the real world, such coloring is called *false coloring*. For example, a gray scale photographic image can be colored for artistic pleasure, and the resulting image is not of natural looking. In contrast, if the image actually has no correlation to any real object in common sense, such coloring is called *pseudo coloring*. For instance, an X-ray image can be colored to make some organs appear more obviously to doctors.

There are many approaches for coloring gray scale images as follows:

4.2.1 Gray-Level-to-Color Transformation

This technique is to assign a color to each gray level. To obtain harmonious colors for adjacent gray levels, the colors assigned must be selected by some methods. The most fundamental guideline is to use colors selected by traversing a smooth path in a color model such as linear interpolation between two colors. Furthermore, to retain the highlights and shadows of an image, the color assigned and the gray level must have equal perceived brightness. A heuristic approach of this technique that fulfills these purposes was designed and applied to this research.

4.2.2 Intensity Slicing

This technique is also called *density slicing* [21] which is a special case of the *gray level to color transformation* technique described above. It can be exploited by partitioning gray levels into ranges and then assigning color to each range.

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[20] Jae S. Lim. Two-Dimensional Signal and Image Processing, pp. 511 - 512.

[21] Rafael C. Gonzalez and Richard E. Woods, Digital Image Processing p. 237.

4.2.3 Filtering Approaches[22]

The techniques of filtering approaches employ the operations in frequency domain. The Fourier transform of an image is altered separately by three filter functions to produce three images that are then fed into red, green, and blue components of the output color image.

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[22] Rafael C. Gonzalez and Richard E. Woods, Digital Image Processing p. 242.