CHAPTER V

QUALITY MEASUREMENT FOR COLOR IMAGES AND APPLICATION IN THIS RESEARCH

Measures for color image quality were developed in this research for measuring the quality of the output images composed by the BW2COLOR software. The color values to be measured, the measures of distortion for these values and their usage will be described in this chapter.

Color Values to be Measured

Each pixel in color images comprises three values: red (R), green (G), and blue (B) while that of gray scale images comprises only a gray level. Thus, the same method for measuring color distortion cannot be applied. Since only the differences of R, G, and B values themselves are not enough in meaning to represent errors, further monitoring of some more parameters is required. Thus, hue (H) and saturation (S) values in the HSV (HSB) and the HLS color model, and perceived brightness (Y) values in the YIQ color model, which are the intuitive notions of colors, were involved. As R, G, and B values should not be considered separately but all together, **RGB** vectors were used to represent the overall data error. Experiments were conducted to test the use of five statistical values: mean error (ME), root mean square error (e_{rms}), e_{rms}/ME percentage,[1] normalized mean error (NME), and normalized mean square error (NMSE), as measures for the distortion of the seven values above.

The definition of an **RGB** vector is presented here. If the color of a pixel on the reference image is (R_1,G_1,B_1) and the color of the same pixel on the distorted image is

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[1] Zahid Hussain, Digital Image Processing Practical Applications of Parallel Processing Techniques (New York, U.S.A.: Ellis Horwood, 1991), pp. 74-76.

(R_2,G_2,B_2), as illustrated in Fig. 5.1, the magnitude of the **RGB** difference vector can be calculated as follows:

$$|\mathbf{RGB}| = \sqrt{(R_2 - R_1)^2 + (G_2 - G_1)^2 + (B_2 - B_1)^2}$$

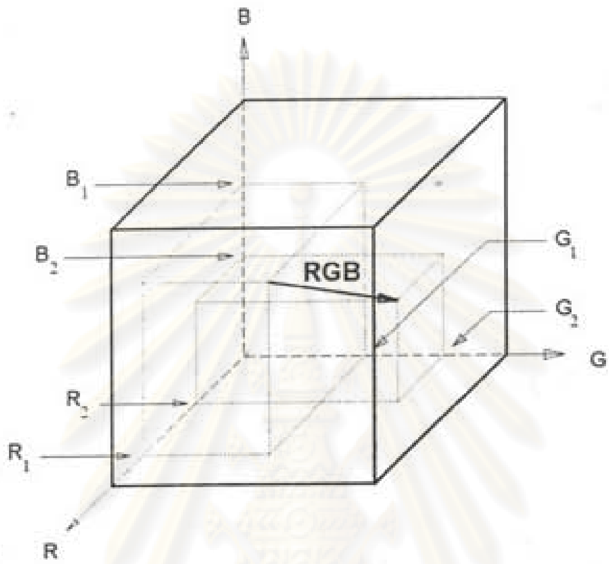

Fig. 5.1 **RGB** vector

Measures of Color Distortion

To measure the color distortion of an image from a reference image, an *error image* must be virtually constructed first by subtracting the value of each corresponding pixel of the distorted image (x_d) from the value of the reference image (x_r), yielding error = $|x_r - x_d|$. Then the following statistical values of the error image and the reference image can then be used as measures of distortion:

1. Mean Error (ME)

   ME is the arithmetic mean of error which can be calculated by:

   For n = number of pixels;

$$ME = \frac{\sum(\text{error})}{n}$$

2. Root Mean Square Error (e_{rms})

   e_{rms} is the root mean square error which can be calculated as follows:

$$e_{rms} = \sqrt{\frac{\sum (\text{error})^2}{n}}$$

3. e_{rms}/ME Percentage

e_{rms}/ME percentage can be calculated by:

$$e_{rms} \text{ / ME percentage } = \frac{e_{rms} \times 100}{\text{ME}} \ (\%)$$

4. Normalized Mean Error (NME)

NME is the percentage of ME divided by the *maximum possible error* as follows:

Maximum possible error = upper-bounded value - lower-bounded value

$$\text{NME} = \frac{\text{ME} \times 100}{\text{maximum possible error}} \ (\%)$$

5. Normalized Mean Square Error (NMSE)

NMSE is the percentage of variance (Var) of the error image divided by variance of the reference image as follows:

For X_i = the value of the pixel number i;

$$\overline{X} = \text{mean of pixel values} = \frac{\sum_{i=1}^{n} X_i}{n}$$

$$\text{Var(error)} = \frac{\sum (\text{error}^2)}{n}$$

$$\text{Var(reference)} = \frac{\sum_{i=1}^{n} (X_i - \overline{X})^2}{n}$$

$$\text{NMSE} = \frac{\text{Var(error)} \times 100}{\text{Var(reference)}} \ (\%)$$

The Test of Five Measures of Color Distortion

Images of monochrome squares of different colors were created to serve as a set of testing data for the application of the five measures above. The results of the experiments are shown in Table 5.1 to 5.5. The distortion of H, S, and Y values represents the human feelings of difference while the distortion of R, G, and B values represents the data errors. Thus, the R, G, and B values presented here range from 0 to 255 as those stored in LUT, not 0 to 1 as those of RGB cubic space unit.

Table 5.1 Reference image: White, Distorted image: Red

	R	G	B	H	S	Y	|RGB|
ME	0	255	255	NA	1	0.70	360.62
e_{rms}	0	255	255	NA	1	0.70	360.62
e_{rms}/ME (%)	NA	100	100	NA	100	100	100
NME (%)	0	100	100	NA	100	70.10	81.65
NMSE (%)	NA	NA	NA	NA	NA	NA	NA

Table 5.2 Reference image: White, Distorted image: Cyan

	R	G	B	H	S	Y	|RGB|
ME	255	0	0	NA	1	0.30	255
e_{rms}	255	0	0	NA	1	0.30	255
e_{rms}/ME (%)	100	NA	NA	NA	100	100	100
NME (%)	100	0	0	NA	100	29.90	57.74
NMSE (%)	NA	NA	NA	NA	NA	NA	NA

Table 5.3 Reference image: Red, Distorted image: Green

	R	G	B	H	S	Y	|RGB|
ME	255	255	0	120	0	0.29	360.62
e_{rms}	255	255	0	120	0	0.29	360.62
e_{rms}/ME (%)	100	100	NA	100	NA	100	100
NME (%)	100	100	0	66.67	0	28.80	81.65
NMSE (%)	NA	NA	NA	NA	NA	NA	NA

Table 5.4 Reference image: Red, Distorted image: Cyan

	R	G	B	H	S	Y	|**RGB**|
ME	255	255	255	180	0	0.40	441.68
e_{rms}	255	255	255	180	0	0.40	441.68
e_{rms}/ME (%)	100	100	100	100	NA	100	100
NME (%)	100	100	100	100	0	40.20	100
NMSE (%)	NA	NA	NA	NA	NA	NA	NA

Table 5.5 Reference image: Cyan, Distorted image: Magenta

	R	G	B	H	S	Y	|**RGB**|
ME	255	255	0	120	0	0.29	360.62
e_{rms}	255	255	0	120	0	0.29	360.62
e_{rms}/ME (%)	100	100	NA	100	NA	100	100
NME (%)	100	100	0	66.67	0	28.80	81.65
NMSE (%)	NA	NA	NA	NA	NA	NA	NA

As an example, the distortion of the |**RGB**| value in Table 5.5 can be calculated as follows:

For cyan; $(R_1, G_1, B_1) = (0, 255, 255)$

For magenta; $(R_2, G_2, B_2) = (255, 0, 255)$

$$\text{error}(|\mathbf{RGB}|) = \sqrt{(R_2 - R_1)^2 + (G_2 - G_1)^2 + (B_2 - B_1)^2}$$
$$= \sqrt{(255-0)^2 + (0-255)^2 + (255-255)^2}$$
$$= \sqrt{255^2 + 255^2}$$
$$= 360.62$$

For n = number of pixels;

$$\text{ME} = \frac{\sum(\text{error})}{n} = \frac{n \times 360.62}{n}$$
$$= \underline{\underline{360.62}}$$

$$e_{rms} = \sqrt{\frac{\sum(\text{error})^2}{n}} = \sqrt{\frac{n \times 360^2}{n}}$$
$$= \underline{\underline{360.62}}$$

$$e_{rms}/\text{ME percentage} = \frac{e_{rms}}{\text{ME}} \times 100\%$$

$$= \frac{360.62}{360.62} \times 100\%$$

$$= \underline{\underline{100\%}}$$

$$\text{Maximum possible error} = \text{upper bounded}\,|\mathbf{RGB}| - \text{lower bounded}\,|\mathbf{RGB}|$$

$$= \sqrt{255^2 + 255^2 + 255^2}$$

$$= \sqrt{3 \times 255^2} = 255\sqrt{3}$$

$$= 441.67$$

$$\text{NME} = \frac{\text{ME}}{\text{maximum possible error}} \times 100\%$$

$$= \frac{360.62}{441.67} \times 100\%$$

$$= \underline{\underline{81.65\%}}$$

$$\text{Var(error)} = \frac{\sum(\text{error}^2)}{n} = \frac{n \times 360.62^2}{n}$$

$$= 360.62^2$$

$$\text{Var(reference)} = \frac{\sum_{i=1}^{n}(|\mathbf{RGB}| - \overline{|\mathbf{RGB}|})^2}{n}$$

$$= 0$$

$$\text{NMSE} = \frac{\text{Var(error)}}{\text{Var(reference)}} \times 100\%$$

$$= \frac{360.62^2}{0} \times 100\%$$

$$= \underline{\underline{\text{Not available}}}$$

It is known that the value of mean error (ME) should always be considered with the *maximum possible error*. However, it is inconvenient to interpret both values as a combined measure of distortion. Thus, more normalized measures, like percentage values of NME or NMSE, may be more appropriate and easier to understand. However, the NMSE percentage is sometimes unavailable when Var(reference) is 0, while the NME percentage is always available as the maximum possible error is always a non-zero value. To measure the variation of error, e_{rms} or e_{rms}/ME percentage may be used. However, e_{rms}/ME percentage is more appropriate since it can be used to compare the variation of error between two different color values while e_{rms} cannot.

Please note that the H value is not available for black, white, and gray colors, so the distortion of H cannot be measured in the cases of Table 5.1 and Table 5.2.

Conclusions on Quality Measurement for Color Images

The two main topics have been discussed in this chapter: which color values should be identified, and which measures should be applied.

In the first place, as the data stored in color image files are (R, G, B) coordinates, the distortion measures on each of the three values represent errors of data. The overall data errors can be measured on **RGB** vectors. To present human feelings of difference, the distortions on H, S, and Y are measured. All the seven color values should be measured and understanding in all color values is necessary in interpreting the measures. For example, distortion of a red square image to a pink square image yields differences on R, S, Y, and $|\mathbf{RGB}|$, and no difference on G and B. It can be said that there are reductions on the amount of the red component, and on the saturation of the red hue. In addition, as more white color is added, the brightness of the image is increased.

In the second place, as the NME measure is available in all cases, and is easier to understand than the combination of ME and the maximum possible error-values, it can be concluded that NME value should be used as measure of distortion for color images. The percentage value of NMSE should not be used as it is sometimes unavailable. However, the e_{rms}/ME percentage should still be noted with NME also, if it is available, as the equal NME's do not mean the equal errors. The more e_{rms}/ME percentage indicates the more variation of error. In the case that the e_{rms}/ME percentage is not available, the e_{rms} value can be used to compare the variation of error for the same color value only.

Quality of Output Images from The BW2COLOR Software

To compare the quality of the color images composed by the BW2COLOR software to the reference images obtained from a color image input device, the quality measurement scheme presented above was exploited. As the dimension and position of two images to be compared must be exactly the same so that each pixel on the distorted image represents the same pixel on the reference image, a HP ScanJet IIc color scanner was used both as an emulated b/w image input device, and as a color image input device.

Five color pictures that vary in color were selected to be sample pictures. The smiling girl, the dog, and the flower pictures are the representations of the pictures in a small number of hues but varied in saturation. The book and the jumping girl pictures are the representations of the pictures which vary in hue. At the same time, the dog, the flower, and the jumping girl pictures can also be the test pictures for red, green, and blue color, respectively. As they cover most variations of hues, these five pictures can be the representations of pictures in most variations of colors.

The calibration card used in the experiment has one white band and 3 gray bands. By adjusting the scanning area to include only some bands, it can be used as if there were 4 calibration cards: one calibration card with one white band, and three calibration cards with one white band and up to three gray bands.

To test the BW2COLOR software with these five pictures, the scanning of the pictures and the calibration card was done for 105 times. Each of the five sample color pictures was scanned three times applying each of the RGB cellophane filters in the gray scale mode to obtain the intensity data and the exposure of each primary color. Each picture was also scanned with no filter applied one time in the gray scale mode to obtain the exposure of the picture and one time in the color mode to obtain the reference color image. The automatic exposure feature of the scanner was exploited every time a picture was scanned. Then, the calibration card was scanned using the same exposures as those set by the automatic exposure feature on scanning the pictures when the consistent filter applied. As it was a time-consuming task, these five images were considered enough for this quality measurement.

The five color images scanned in color mode (a) in comparison to those composed by the BW2COLOR software using a calibration card with white band and three other gray bands (b) are shown in Fig. 5.2 to 5.6.

(a) b)

Fig 5.2[*] The smiling girl images

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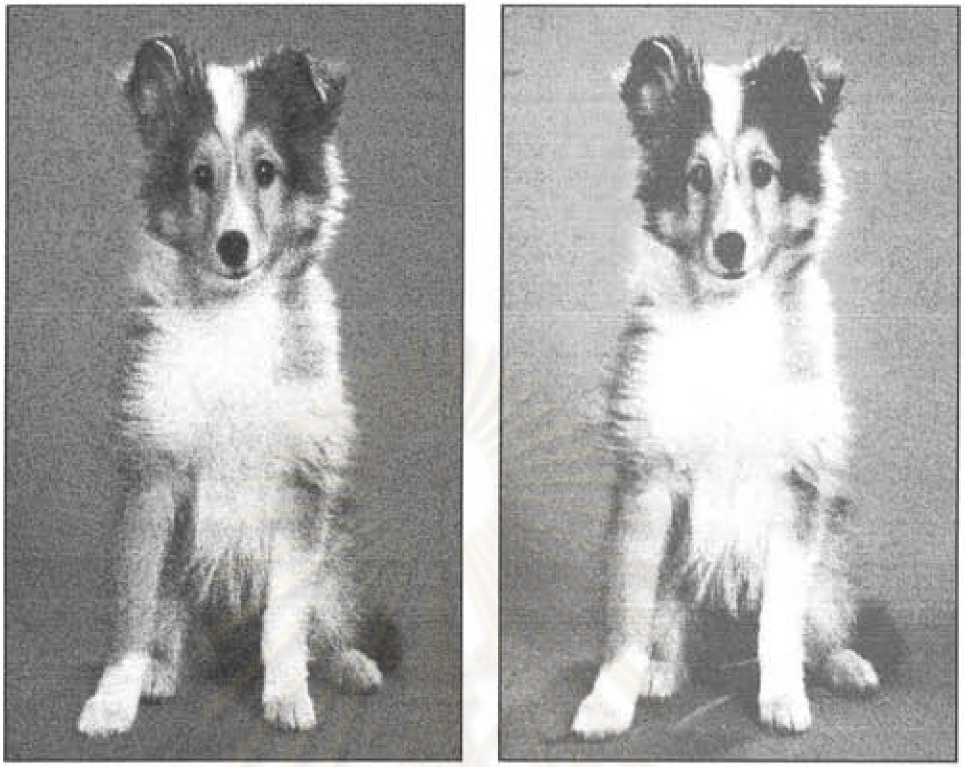
[*] The smiling girl images were from a calendar card produced by Mangpong Co., Ltd., Thailand in 1994.



(a) (b)

Fig 5.3* The dog images

(a) (b)

Fig. 5.4** The flower images

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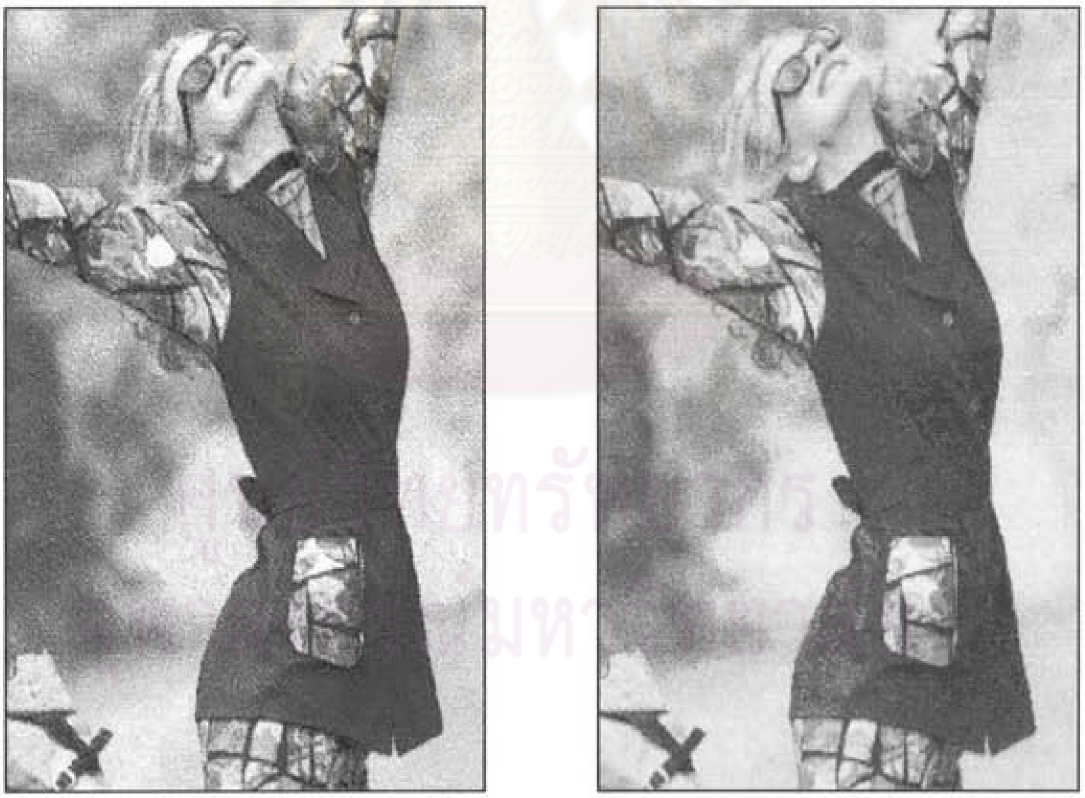
* The dog images were from a calendar produced by Hallmark Cards, Inc., U.S.A. in 1984.

** The flower images were from a calendar.

(a) (b)

Fig. 5.5* The book images



(a) (b)

Fig. 5.6** The jumping girl images

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* The book images were from a magazine advertisement.

** The jumping girl images were from a magazine.

For the reasons already mentioned in the previous section. NME was used as the measure of color distortion on seven values: R, G, B, H, S, Y, and |**RGB**|. The e_{rms}/ME percentage was also used to represent the variation of error. The NME and the e_{rms}/ME percentage of each of the seven color values of all the five images are shown in Table 5.6 to 5.12. Please note that the error caused by wrinkles on the cellophane filters were included.

Table 5.6 NME (R)

LUT	Number of grays	NME (R) (%)					Average NME (R) (%)	Average e_{rms}/ME (R) (%)
		Image 1	Image 2	Image 3	Image 4	Image 5		
fixed	1	6.89	14.33	13.30	7.91	9.45	10.38	140.56
unfixed	1	8.51	13.67	12.73	3.89	9.44	10.25	122.72
	2	5.75	12.10	7.89	8.60	17.00	10.27	135.45
	3	5.32	7.59	NA	7.73	NA	6.88	140.86
	4	5.44	7.59	6.40	6.18	20.57	9.24	139.22

Table 5.7 NME (G)

LUT	Number of grays	NME (G) (%)					Average NME (G) (%)	Average e_{rms}/ME (G) (%)
		Image 1	Image 2	Image 3	Image 4	Image 5		
fixed	1	9.61	16.06	12.15	9.08	8.68	11.12	144.73
unfixed	1	8.74	18.11	12.26	7.66	8.85	11.12	134.64
	2	10.51	24.29	14.13	7.89	11.73	13.71	127.48
	3	10.10	24.64	NA	8.16	NA	14.30	123.58
	4	12.01	25.41	13.64	9.51	9.53	14.02	124.69

Table 5.8 NME (B)

LUT	Number of grays	NME (B) (%)					Average NME (B) (%)	Average e_{rms}/ME (B) (%)
		Image 1	Image 2	Image 3	Image 4	Image 5		
fixed	1	41.47	39.20	35.17	26.35	16.84	31.81	121.22
unfixed	1	39.94	39.33	34.76	25.44	16.69	31.23	120.59
	2	52.85	49.40	43.98	36.93	21.35	40.90	116.62
	3	42.89	39.32	NA	34.47	NA	38.23	177.93
	4	31.51	49.38	27.08	27.52	16.43	30.38	113.41

Table 5.9 NME (H)

LUT	Number of grays	NME (H) (%)					Average NME (H) (%)	Average e_{rms}/ME (H) (%)
		Image 1	Image 2	Image 3	Image 4	Image 5		
fixed	1	52.28	33.39	43.14	42.11	40.72	42.33	124.16
unfixed	1	52.24	39.05	43.05	58.37	51.41	48.82	116.94
	2	54.07	25.88	43.37	37.95	30.50	38.43	121.62
	3	49.98	18.04	NA	42.57	NA	36.85	121.27
	4	32.04	27.21	31.58	31.72	31.24	30.76	132.56

Table 5.10 NME (S)

LUT	Number of grays	NME (S) (%)					Average NME (S) (%)	Average e_{rms}/ME (S) (%)
		Image 1	Image 2	Image 3	Image 4	Image 5		
fixed	1	52.55	42.32	47.05	22.62	26.65	38.24	121.31
unfixed	1	55.18	43.53	45.65	23.81	26.38	38.91	117.14
	2	57.84	37.65	46.45	21.08	28.42	38.29	119.24
	3	54.94	40.00	NA	22.58	NA	39.17	117.40
	4	48.86	41.43	40.71	33.99	37.47	40.49	113.09

Table 5.11 NME (Y)

LUT	Number of grays	NME (Y) (%)					Average NME (Y) (%)	Average e_{rms}/ME (Y) (%)
		Image 1	Image 2	Image 3	Image 4	Image 5		
fixed	1	10.50	11.36	9.74	8.31	7.79	9.54	128.27
unfixed	1	8.91	12.17	9.15	6.81	7.57	8.92	127.57
	2	12.93	23.39	14.80	10.04	13.41	14.91	117.35
	3	11.17	21.03	NA	8.26	NA	13.49	121.41
	4	11.51	22.63	11.45	8.93	10.18	12.94	117.72

Table 5.12 NME (|**RGB**|)

LUT	Number of grays	NME (|**RGB**|) (%)					Average NME (|**RGB**|) (%)	Average e_{rms}/ME (|**RGB**|) (%)
		Image 1	Image 2	Image 3	Image 4	Image 5		
fixed	1	26.46	27.23	24.76	18.84	14.80	22.42	112.54
unfixed	1	24.81	27.23	23.87	17.38	14.41	21.54	112.63
	2	32.72	33.24	28.26	23.71	19.24	27.23	111.00
	3	26.20	27.97	NA	21.42	NA	25.20	113.53
	4	20.45	32.94	19.31	18.49	18.11	20.86	107.83

The average NME values from the seven tables above are summarized again in Table 5.13 for a better comparison.

Table 5.13 Average NME values

LUT	Number of grays	Average NME (%)							Number of samples
		R	G	B	H	S	Y	|**RGB**|	
fixed	1	10.38	11.12	31.81	42.33	38.24	9.54	22.42	5
unfixed	1	10.25	11.12	31.23	48.82	38.91	8.92	21.54	5
	2	10.27	13.71	40.90	38.43	38.29	14.91	27.23	5
	3	6.88	14.30	38.23	36.85	39.17	13.49	25.20	3
	4	**9.24**	**14.02**	**30.38**	**30.76**	**40.49**	**12.94**	**20.86**	5

Though the composed images with fixed LUT's have only slightly greater NME's, the transitions or contours between colors are much more conspicuous to viewers.

To compare the effects of the number of gray bands on the color distortion, the graphs of the average of the seven values are shown in Fig. 5.7 to 5.13. The only conclusion that can be made on these graphs is that, adding more gray bands to the calibration card tends to result in less distortion on hue (H).

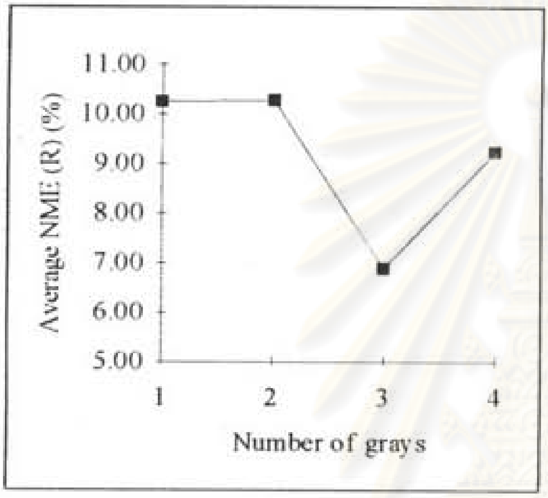

Fig. 5.7 Average NME (R)

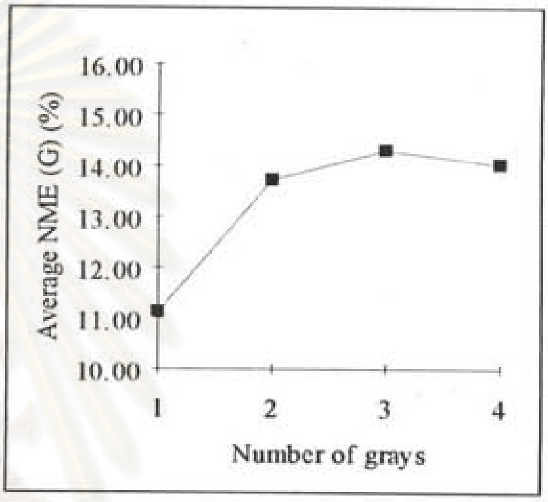

Fig. 5.8 Average NME (G)

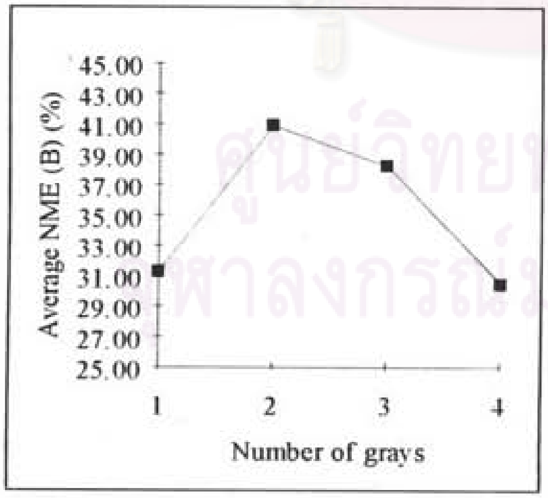

Fig. 5.9 Average NME (B)

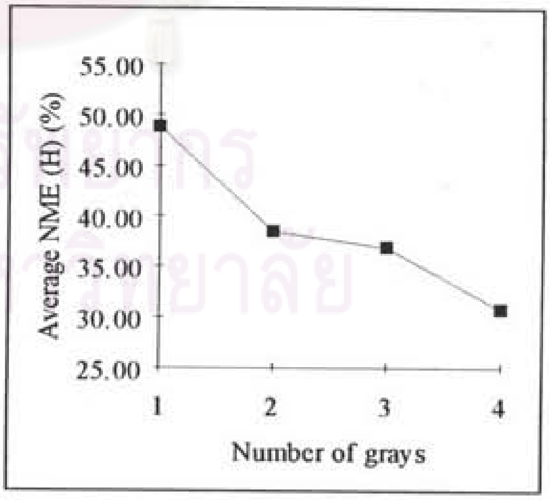

Fig. 5.10 Average NME (H)

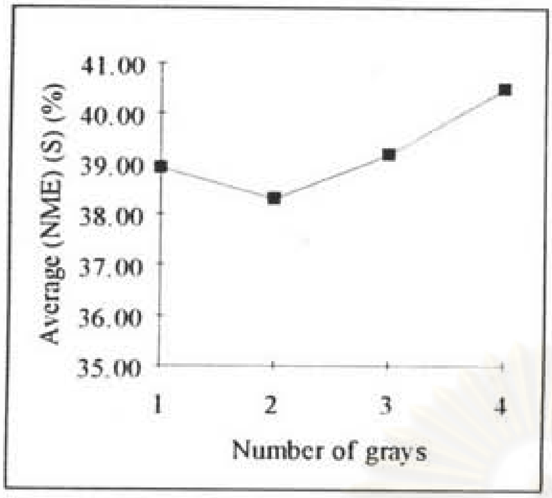

Fig. 5.11 Average NME (S)

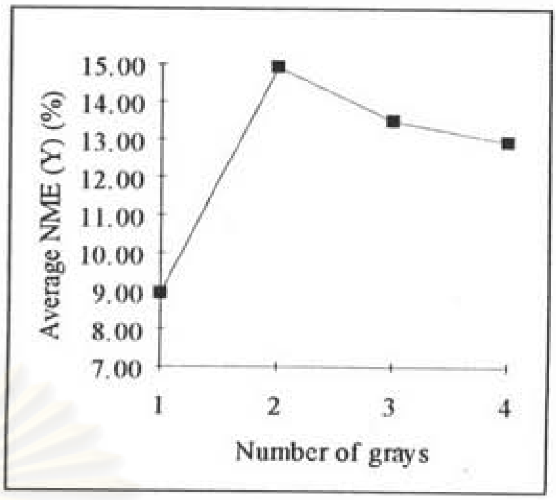

Fig. 5.12 Average NME (Y)

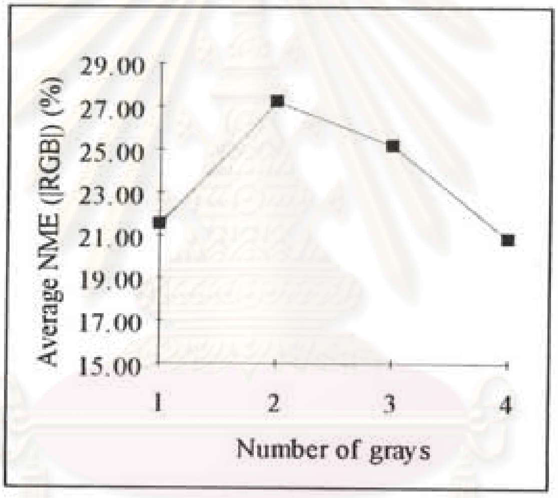

Fig. 5.13 Average NME (|**RGB**|)

As already mentioned in Chapter III, the NME of |**RGB**| values is the best measure for representing the overall color distortion. It can be stated here that the average errors of the five color images composed by the BW2COLOR software in comparison to the color images obtained from the color scanner are 20.86% for the unfixed LUT and 22.42% for the fixed LUT, when a calibration card with four gray bands and a set of RGB cellophane filters are applied. The variations of error (e_{rms}/ME percentage) are 107.83% for the unfixed LUT and 112.54% for the fixed LUT. It can be concluded that the unfixed LUT yields the output color images of better color quality. It is noted again that the errors caused by wrinkles on the cellophane filters and by the limitation of the image input software were also included.

In an experiment, light red cellophane was used instead of red cellophane. The results are shown in Table 5.14 to 5.20, and the average values are summarized in Table 5.21.

Table 5.14 NME (R) when light red cellophane is applied

LUT	Number	NME (R) (%)					Average	Average
	of grays	Image 1	Image 2	Image 3	Image 4	Image 5	NME (R) (%)	e_{rms}/ME (R) (%)
fixed	1	3.82	16.68	15.62	7.78	10.92	10.96	149.34
unfixed	1	7.61	17.33	15.22	6.94	11.13	11.65	120.43
	2	6.94	12.43	7.41	9.15	10.25	9.24	135.42
	3	6.79	13.44	NA	9.42	NA	9.88	134.14
	4	8.00	20.66	7.67	7.95	16.66	12.19	135.31

Table 5.15 NME (G) when light red cellophane is applied

LUT	Number	NME (G) (%)					Average	Average
	of grays	Image 1	Image 2	Image 3	Image 4	Image 5	NME (G) (%)	e_{rms}/ME (G) (%)
fixed	1	9.61	16.06	12.15	9.08	8.68	11.12	144.73
unfixed	1	8.74	17.98	12.26	7.68	8.85	11.10	134.70
	2	10.51	24.16	14.13	7.19	11.72	13.54	127.53
	3	10.10	24.51	NA	8.18	NA	14.26	123.67
	4	12.10	25.21	13.64	9.54	9.52	14.00	124.75

Table 5.16 NME (B) when light red cellophane is applied

LUT	Number	NME (B) (%)					Average	Average
	of grays	Image 1	Image 2	Image 3	Image 4	Image 5	NME (B) (%)	e_{rms}/ME (B) (%)
fixed	1	41.47	39.20	35.17	26.35	16.84	31.81	121.22
unfixed	1	39.94	39.33	34.76	25.44	16.69	31.23	120.58
	2	52.85	49.40	43.98	36.93	21.33	40.90	116.02
	3	42.89	39.33	NA	32.47	NA	38.23	117.93
	4	31.51	49.87	27.09	27.51	16.42	30.48	113.56

Table 5.17 NME (H) when light red cellophane is applied

LUT	Number of grays	NME (H) (%) Image 1	Image 2	Image 3	Image 4	Image 5	Average NME (H) (%)	Average e_{rms}/ME (H) (%)
fixed	1	54.51	37.20	45.51	38.31	48.03	44.71	123.24
unfixed	1	53.11	45.88	44.46	25.44	57.46	45.27	115.33
	2	52.58	26.17	45.25	37.62	38.57	40.04	119.93
	3	47.40	16.54	NA	41.14	NA	35.03	122.06
	4	29.44	21.05	24.64	28.73	28.94	26.56	135.10

Table 5.18 NME (S) when light red cellophane is applied

LUT	Number of grays	NME (S) (%) Image 1	Image 2	Image 3	Image 4	Image 5	Average NME (S) (%)	Average e_{rms}/ME (S) (%)
fixed	1	60.77	43.03	46.05	22.87	26.39	39.82	125.12
unfixed	1	57.93	44.41	44.06	23.90	25.74	39.21	118.75
	2	56.01	37.61	45.55	21.05	24.71	36.99	119.62
	3	51.96	36.54	NA	22.44	NA	36.98	117.28
	4	44.75	34.91	41.14	36.17	36.16	38.63	113.86

Table 5.19 NME (Y) when light red cellophane is applied

LUT	Number of grays	NME (Y) (%) Image 1	Image 2	Image 3	Image 4	Image 5	Average NME (Y) (%)	Average e_{rms}/ME (Y) (%)
fixed	1	9.49	10.81	8.72	8.62	7.61	9.05	125.89
unfixed	1	8.59	11.28	8.31	6.96	7.29	8.49	126.50
	2	13.40	23.36	11.45	10.27	11.41	13.98	118.31
	3	11.79	22.84	NA	8.90	NA	14.51	120.55
	4	12.68	26.58	12.64	7.76	9.19	13.77	119.21

Table 5.20 NME (|**RGB**|) when light red cellophane is applied

LUT	Number of grays	NME (|**RGB**|) (%) Image 1	Image 2	Image 3	Image 4	Image 5	Average NME (|**RGB**|) (%)	Average e_{rms}/ME (|**RGB**|) (%)
fixed	1	26.13	27.72	25.20	18.82	55.32	30.64	111.81
unfixed	1	24.70	27.96	24.41	17.42	52.69	29.44	111.93
	2	31.88	33.24	28.02	23.84	52.75	33.95	111.53
	3	26.44	28.84	NA	21.79	NA	25.69	113.14
	4	21.03	35.46	19.71	18.85	41.19	27.25	107.64

Table 5.21 Average NME when light red cellophane is applied

LUT	Number of grays	Average NME (%)							Number of samples
		R	G	B	H	S	Y	**|RGB|**	
fixed	1	10.96	11.12	31.81	44.71	39.82	9.05	30.64	5
unfixed	1	11.65	11.10	31.23	45.27	39.21	8.49	29.44	5
	2	9.24	13.54	40.90	40.04	36.99	13.89	33.95	5
	3	9.88	14.26	38.23	35.03	36.98	14.51	25.69	3
	4	**12.19**	**14.00**	**30.48**	**26.56**	**38.63**	**13.77**	**27.25**	5

In comparison to those output images when red cellophane is applied, light red cellophane yields higher distortion on the red (R) component as it allows more green and blue light to pass through (see Table 5.6 and Table 5.14). The overall color distortion represented by NME(|**RGB**|) is 27.25% in average when light red cellophane is applied, higher than the average 20.86% when red cellophane is applied. The variations of error (e_{rms}/ME percentage) are 107.64% for the light red cellophane and 112.54% for the red cellophane. The result of the experiment suggests that a light red cellophane may be applied as a red filter, however it will result in the higher distortion on the red component.

In summary, the color distortion was measured by normalized mean error (NME) on the magnitude of **RGB** difference vectors. The unfixed LUT reveals the output images of better color quality than the fixed LUT, with the average color distortion of 20.86% and 22.42%, respectively. The light red cellophane filter may be used instead of the red cellophane filter, however, yielding higher color distortion on the output color images, with the average color distortion of 27.25%.