COLOR CONSISTENCY BETWEEN DIFFERENT PRINTING MATERIALS USING DOT GAIN AND INTENSITY COMPENSATION

Cheol-Hee Lee[1], Chae-Soo Lee[2], and Yeong-Ho Ha[1]

School of Electronic and Electrical Eng.[1]
Kyungpook National University, Taegu 702-701, Korea

Department of Computer Information Eng.[2]
Kyungwoon University, Gumi 730-850, Korea

Abstract - In a drop-on-demand thermal ink-jet printer, the dot size of an ink droplet expelled from a printer depends on the absorption ratio of the substrate. This causes color differences between output images on different printing materials. In this paper, a color consistency algorithm for different papers is proposed. To achieve a corresponding color reproduction, dot gain compensation based on saturation was applied to correct the color reproduction of the printer. However, dot gain compensation applied to substrates with different intensity values may still produce unequel intensity values in the output images. Accrodingly, intensity compensation is added in order to match the colors of different papers.

1. INTRODUCTION

The absorption ratio of ink will vary according to the paper used for printing. In addition, surface coating used for better printing quality also produces a different absorption ratio for the same substrate. In digital printing with an ink-jet printer, the ink and substrate interaction is a very important factor. In most reproduction device, the halftone dots that are generated will grow on the printing paper. This growth is called dot gain. Basically, there are two types of dot gain, mechanical and optical dot gain[1]. In the case of mechanical dot gain, low ink viscosity is the major cause for overlap between neighboring ink dots. As a result, this causes unwanted color and reduces the brightness of the prints through the spread of ink droplets to adjacent areas which should remain white. Takahashi and Fujita have studied mechanical dot gain in offset printing on the microscopic scale[2].

Optical dot gain is due to a combination of the poor frequency resolution of the human eye and the scattering effect of the substrate. The limited frequency resolution of the eye only permits us to see gray in a dither matrix instead of halftone macrodots of black and white, plus the light scattering in a substrate creates a halo around the halftone dots that are only partially printed with ink. Accordingly, the printed area perceived by the HVS(human visual system) and a densitometer is actually larger than the original area covered by ink.

Many studies have been conducted to assess the interaction between ink and paper. Murray and Davies estimated reflectance via the absorption of halftone dots without considering the scattering in the paper. Yule and Nielsen considered both light penetration and scattering under the assumption that the light was completely diffused by the paper. Thereafter, Yule with Clapper developed a more accurate halftone process based on an analysis of multiple scattering, internal reflection, and transmission[3].

This paper proposes a method for producing color consistency between different paper materials using dot gain and intensity compensation. To produce color consistency between papers, dot gain is assessed by the saturation of color patches. The dot gain of standard paper was assumed to be negligible, therefore, the dot gain of the paper which is to be compensated was assessed. These saturation values can be obtained by measuring the color patches with a MCPD(multi-channel photo detector). To generate a full saturation range for a printer, color patches ranging from the minimum to the maximum color levels are printed for each primary ink.

When selecting the color space to identify the saturation of the color patches, HSI, HSV, and YIQ color space were studied. Plus, when cosidering saturation changes in relation to the amount of ink and printer resolution, the amounts of ink and printer resolutions were changed for each substrate. The tristimulus values, obtained from the measurement of the color patches, were converted to saturation in the three color spaces mentioned above. After dot gain compensation, the intensity of an output image can change. This problem is not only due to dot gain compensation, but also related to the difference of intensity between papers. The intensities of pure substrates are not the same due to their unique spectral reflectance. Accordingly, intensity compensation is proposed to simultaneously compensate for both of the above problems, as this equation will predict the average intensity of the printed image after dot gain compensation.

2. MEASUREMENT OF SPECTRAL REFLECTANCE OF COLOR PATCHES

Contributed Paper

Manuscript received April 12, 1999

In a subtractive mixture, color is generated by a combination of cyan, magenta, and yellow (CMY) inks. These primary inks behave as a filter to incident lights, and produce their own envelope of spectral reflection for each incident ray wavelength [4]. Therefore, incident lights on a substrate with embedded ink particles are absorbed or reflected by the ink particles. After interaction with these particles, the amounts of reflected lights from the substrate decrease so that the light perceived by the HVS has a low intensity compared to the incident lights. When all primary inks are mixed, most incident lights are absorbed by the ink particles and the reflected lights are nearly black. After interaction in the substrate, the reflected lights perceived by HVS are defined as

$$\rho^x = \int E^x(\lambda) S^x(\lambda) R(\lambda) d\lambda \tag{1}$$

In the above equation, $E^x(\lambda)$ is the distribution of the spectral reflectance of incident lights at position x, $S^x(\lambda)$ is the surface reflectance of an object, and $R(\lambda)$ represents the spectral sensitivity of a visual system to a color signal, $E^x(\lambda)R(\lambda)$. Therefore, in the case of light irradiation on the same substrates, if $R(\lambda)$ changes due to a different type of coating or printing on the surface of the substrate, the color signal perceived by the HVS will different. Color halftoning in an ink-jet printer, is also based on generating color using the subtractive mixture theory.

However, in reality black ink(K) is also required as, although multicolor printing using CMY inks can theoretically produce the color black, a long dry-time is needed for a substrate, the color produced is more of a dark gray, and it lacks any hue component. In quadrichromic printing (CMYK primaries), a pixel is produced using a combination of CMYK primaries. An image generated by CMYK can be written as

$$P_{i,j} = \sum_{k=1}^{h}\sum_{l=1}^{v}(b_{k,l}^{C}, b_{k,l}^{M}, b_{k,l}^{Y}, b_{k,l}^{K}) \tag{2}$$

$$I = \sum_{i=1}^{H}\sum_{j=1}^{V} P_{i,j} \tag{3}$$

where, h and v are the horizontal and vertical widths of a dither matrix, respectively. $P_{i,j}$ is a pixel represented by the dither matrix. Here, $b_{k,l}$ indicates whether or not a dot grid of the dither matrix will be marked by an ink at position k, l in the pixel, $P_{i,j}$. H and V represent the widths of an image, I in the row and column direction respectively. When printing an image on a CRT, if the resolution of the CRT is between 72dpi to 80dpi, a pixel from the input image can be represented by a 4×4 dither matrix without changing the image size for a 300dpi printing resolution [5].

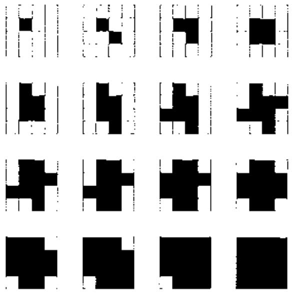
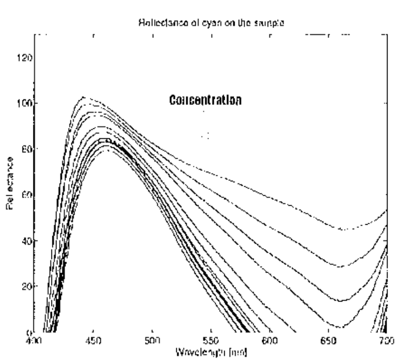


Fig. 1. Ideal 4×4 dither matrix

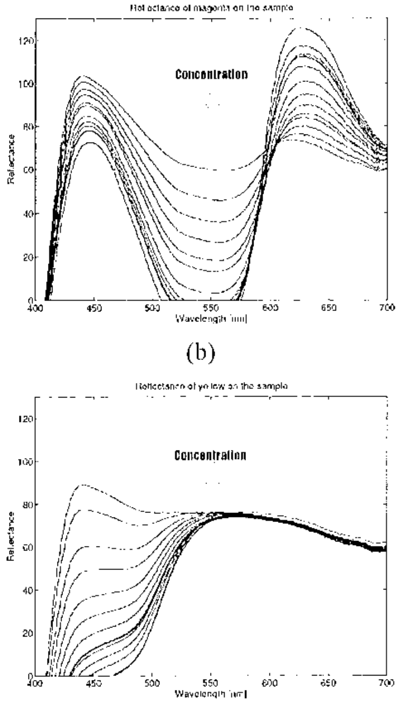
Fig. 1 represents an ideal AM(amplitude modulation) dither matrix in which the grids are printed in spiral order. In a real ink-jet printer, each dot droplet expelled from the printer creates a filled irregular shape shape like an ellipse. Thereafter, this dot size will increase from the initial droplet size in accordance with the absorption ratio of a particular ink with a particular substrate. This often results in an ink overlap onto neighboring pixels and produces an unwanted color. Therefore, in order to maintain color consistency between different substrates, a compensation process is needed.

The proposed compensation algorithm for controlling ink dot gain is based on the measurement of color patches. Using these measurements, the digital inking values for a substrate are compensated backwards. Adithering pattern of color patches is displayed in Fig. 1.

A tungsten-halogen lamp was used as the standard illumination in the measurement of the color patches. A light from the illumination was projected through an optical fiber onto a color patch at 45° inside a sample measurement unit. Next, a detector of MCPD senses the reflected light from a color patch at 90° (CIE recommendation 3, 1931). The spectral reflectances of the color patches were as follows.



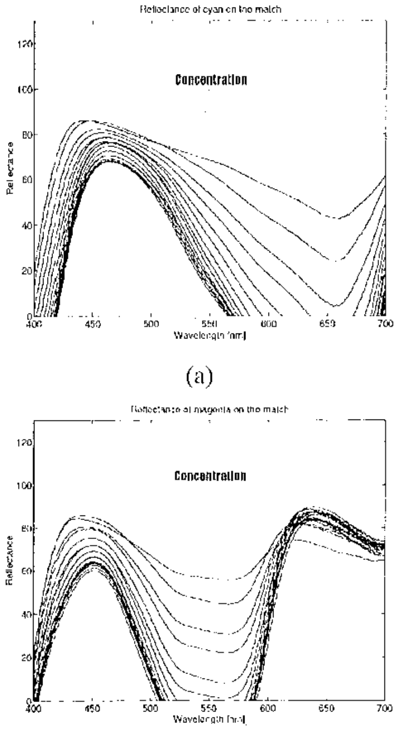
(a)



(b)

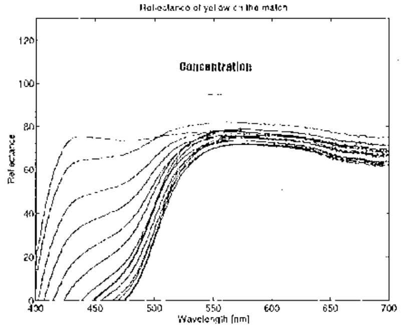
(c)

Fig. 2. Spectral reflectance of primary ink printed on glossy paper (a) cyan (b) magenta (c) yellow.



(a)

(b)



(c)

Fig. 3. Spectral reflectance of primary ink printed on coated paper (a) cyan (b) magenta (c) yellow.

Fig. 2 and 3 illustrate the spectral reflectance of color patches in accordance with varied amounts of primary inks. For the color patches made with glossy paper and their corresponding color patces made with coated paper, as the number of marked dots in the dither matrix increase the spectral reflectance of the color patches bore a stronger resemblance to the spectral reflectance of the ink itself. The reflection ratio for glossy paper was higher than that for coated paper for all visible ray wavelengths. This indicates that glossy paper has a higher reflectance to incident lights.

3. THE COMPARISON FOR THE DYNAMIC RANGE OF SATURATION IN THREE COLOR SPACES AND COLOR SPACE SELECTION

Color, as perceived by the HVS system, can be objectively defined using a color coordinate system. To provide such a objective color description, several three-component color spaces have been developed by the C.I.E.(Commission Internationale de l'Eclairage). However, there is no single color space that satisfies all the requirements needed in color image processing. Therefore, colorists are forced to choose the appropriate color space to meet their specific purposes. In this study, three color spaces, HSI, HSV, and YIQ are used to measure the saturation values of color patches [6-8]. The tristimulus values of color patches obtained from a MCPD were thus transformed into a saturation signal in these color spaces.

The results indicated that the change of saturation in relation to a linear increase in the amount of an ink was nonlinear. As the amounts of ink on both papers increase, the saturation of a color patch also increased monotonically. The dynamic range of saturation in these color spaces is shown in Table 1. A dynamic range refers to the difference between the maximum and minimum

saturation for a color patches. To use of saturation as an effective measure for estimating changes in a printed area, requires a distinguishable color space that includes a wide dynamic range for saturation.
Based on Table 1, the HSI color space was chosen to obtain the saturation values for color patches because it offered a greater dynamic range of saturation regardless of ink and printing resolution on the substrate materials.

Table 1. The comparison of normalized dynamic ranges for saturation among color spaces.

a) 51625A, 300dpi, the glossy paper
b) 51625A, 300dpi, the coated paper
c) 51649A, 600dpi, the glossy paper
d) 51649A, 600dpi, the coated paper

	HSI	HSV	YIQ
Cyan	0.745	0.567	0.251
Magenta	0.760	0.586	0.346
Yellow	0.978	0.950	0.256
Average	0.827	0.701	0.284

(a)

	HSI	HSV	YIQ
Cyan	0.779	0.627	0.267
Magenta	0.771	0.639	0.264
Yellow	0.965	0.944	0.250
Average	0.838	0.737	0.260

(b)

	HIS	HSV	YIQ
Cyan	0.841	0.677	0.245
Magenta	0.841	0.685	0.227
Yellow	0.982	0.955	0.250
Average	0.888	0.772	0.241

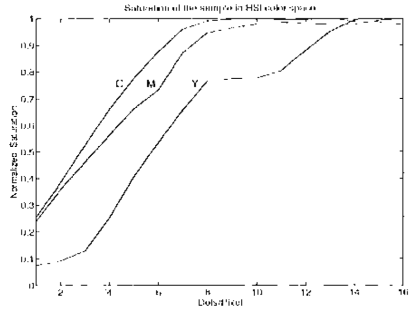
(c)

	HIS	HSV	YIQ
Cyan	0.890	0.759	0.273
Magenta	0.833	0.731	0.228
Yellow	0.960	0.932	0.260
Average	0.894	0.807	0.254

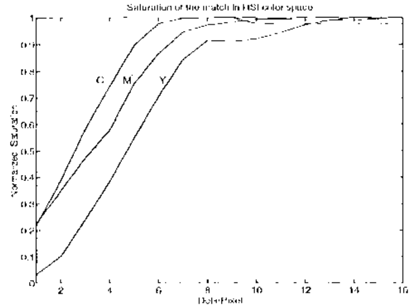
(d)

4. DOT GAIN COMPENSATION BASED ON SATURATION

The tristimulus values, obtained from the measurement for color patches, were transformed into a saturation signal in the HSI space. For both glossy and coated substrates, as the number of marked dots per pixel increased, the corresponding saturation also increased monotonically. Graphs of the saturation distribution of primaries on both substrates are displayed in Fig. 4.



(a) sample



(b) match

Fig. 4. Saturation corresponds to the amounts of the primaries.

Using the two graphs in Fig 4, a dot gain compensation algorithm with two stages is proposed.

4.1 Dot gain compensation using the saturation ratios for the same inks

As the substrate absorption ratio of an ink increases, the dot size will also increase. Accordingly, as the dot size increases, the white background in the color patch will decrese, and the ligth reflected in the sample measurement unit will include a lower white signal. As a result this heightens the purity of the color signal detected in a MCPD. In Fig. 4, a match with a lower spectral reflectance exhibits a higher saturation over a wider range. Particularly in the linear region, the slope of the match is higher than that of the sample. Therefore, primary inks on the coated paper can be compensated by the saturation ratio between the two substrates. A color represented by the primaries is defined as

$$I_{i,j} = [C_{i,j}, M_{i,j}, Y_{i,j}] \tag{4}$$

After compensation with the relative ratio of saturation, the revised color is given as

$$I'_{i,j} = \left[\frac{S_s(C_{i,j})}{S_m(C_{i,j})} C_{i,j},\ \frac{S_s(M_{i,j})}{S_m(M_{i,j})} M_{i,j},\ \frac{S_s(Y_{i,j})}{S_m(Y_{i,j})} Y_{i,j} \right] \tag{5}$$

In the above equation, s and m represent the sample and the match, respectively. And $S_s(C_{i,j})$ is the saturation value of a glossy color patch printed with cyan ink where $C_{i,j}$ is the number of dots per pixel. Using Eq. (5), the primaries on coated paper can be compensated by multiplying the saturation ratio of the sample with the matching primary components such as $C_{i,j}$.

4.2 Dot gain compensation using the distribution of the maximum saturation.

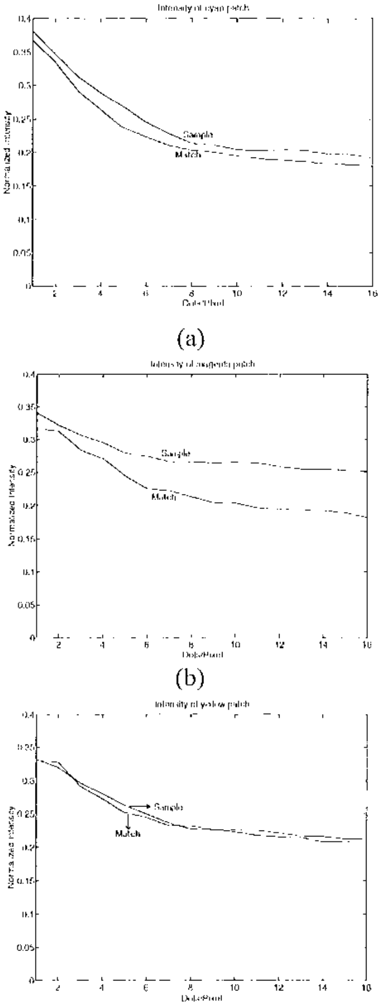
In Fig. 4, the saturation values for lower amounts of primary inks increase almost linearly. These values start to maintain maximum levels from the mid-level amounts of the C, M, and Y components. In our experiment, the starting points for the maximum saturation values were 9, 16, and 14 on coated paper, and 13, 16, and 15 on glossy paper for cyan, magenta, and yellow, respectively. Magenta ink exhibited the same maximum saturation value with the same amount of ink regardless of the substrate. However, cyan and yellow inks exhibited differing maximum saturation values with different amounts of ink. Specifically, cyan displayed its peak at 9 dots per pixel on coated paper. This means that the dot gain for cyan on coated paper is much larger than that of other inks. If there is no compensation, this extensive dot gain for cyan produces a mixture with the inks of neighboring pixels and results in a printed image with a bluish tone over the entire area of coated paper. In this experiment, the distribution of the starting points of maximum saturation for cyan and magenta inks was dependent on the substrate material. To match colors on different substrates, it is important to balance the distribution of the maximum saturation values of primary inks on glossy paper with that on coated paper. To obtain this balance, the primaries on coated paper can be compensated as follows.

$$I''_{i,j} = \left[\left(\frac{L-d_C}{L}\right) C'_{i,j},\ \left(\frac{L-d_M}{L}\right) M'_{i,j},\ \left(\frac{L-d_Y}{L}\right) Y'_{i,j} \right] \qquad (6)$$

where L is the maximum value of the ink components, which was 16 in our experiments, and (d_C, d_M, d_Y) represents the starting point differences for the maximum saturation value, which in our experiments were 3, 0, and 1 for cyan, magenta, and yellow, respectively. Using Eq.(6), the digital inking values for cyan and magenta on coated paper can be revised without changing digital inking value for magenta.

5. INTENSITY MATCHING USING THE ESTIMATION OF AN AVERAGE INTENSITY OF AN IMAGE ON A SUBSTRATE

As mentioned previously, the intensity values of two pure substrates will not be the same. For example, the intensity of glossy paper, which has a higher spectral reflectance, is higher than that of coated paper. In our experiment, the intensity values of two substrates used were 0.390 and 0.377 for glossy and coated papers, respectively. Moreover, dot gain compensation can cause a change in the average intensity of a resultant image on coated paper. As seen in Eqs. (5) and (6), dot gain compensation directly changes the digital inking values of the primaries. Accordingly, in order to correctly match the intensity between images printed on different substrates, an intensity compensation process is required that can take account of a change of intensity during dot gain compensation and the difference of intensity between two substrates.



(a)

(b)

(c)

Fig. 5. The intensity distribution of color patches in

relation to the number of primary color printed dots:
(a) cyan (b) magenta (c) yellow.

Fig. 5 represents intensity changes in color patches in relation to the number of printed dots in a pixel. For both sets of color patches, as the amount of ink incresed, the intensity of the color patch decreased monotonically. Also, the intensity value of the sample was higher than that of its match across almost the whole range, regardless of the amount of primary ink. This figure is a good illustration of intensity changes related to the amounts of ink. Based on Fig. 5, it is possible to formulate an equation to predict the average intensity of an output image. Using the equation, the interim average intensity for an output image is predicted as,

$$\bar{I} = \frac{1}{HV} \sum_{i=1}^{H} \sum_{j=1}^{V} \left\{ I_k - (I_k U - I''_{i,j})^T U \right\} + I_o \tag{7}$$

where I_k is the intensity value of unprinted glossy or coated paper, and I represents the defined signals in HSI space. U is the matrix, $[I, I, I]^T$, and I_o is the offset intensity value. When color patches are tripple-printed with CMY using 16 dots per pixel on both glossy and coated papers, the intensities of the matches are all lower and negative. Therefore, I_o is the value that sets the intensity of the match fully printed by primaries to zero. Once I_o is decided, it remains fixed. In Eq. (7), $I_k U - I''_{i,j}$ represents the decrease in intensity in a printed pixel at position (i,j) compared to the original intensity of the substrate itself. In other words, this indicates the intensity reduction caused by printed ink. Therefore, the intensity of a pixel can be obtained by subtracting the intensity reduction from the original intensity of the substrate. In addition, the average intensity of an image can be obtained by finding the mean of all pixels.

In real-life printing, however, the overall decrease in intensity caused by multiple ink is not a linear sum of the decreased intensities caused by each individual ink. To identify the precise intensity of a color patch, it is important to consider all cases for printed primaries. In the case of n-bit color reproduction in multiple ink printing, the number of all combinations is $2^{n \times m}$, accrodingly, a look up table with measured intensity values for all $2^{n \times m}$ combinations are needed where m is the number of primary ink. In Eq. (7), it is assumed that the overall decrease of intensity in multiple ink printing is the linear sum of the three decreased intensities caused by each ink. Based on this assumption, the use of Eq. (7) makes it possible to predict the average intensity of an image and the intensities of 48 color patches. The intensity minimization process between images on coated and glossy papers is included in Fig. 6.

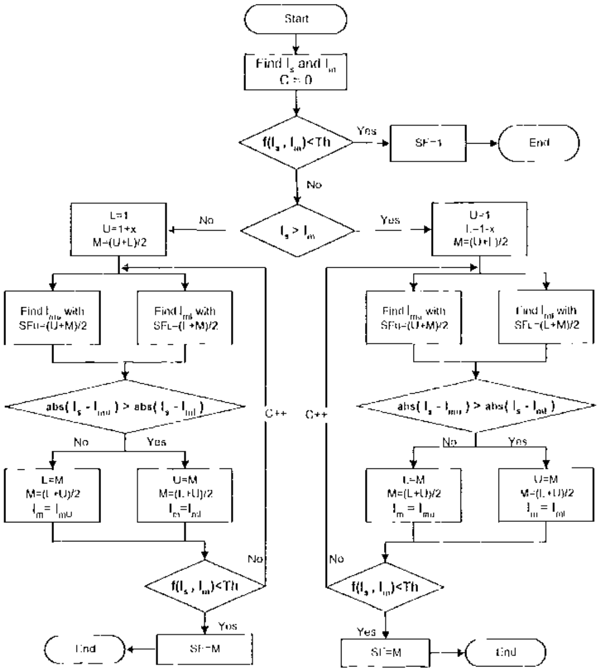


Fig. 6. Flow chart of intensity compensation in a match

In Fig. 6, I_s is the predicted intensity of an input image on glossy paper and I_m represents the predicted intensity of a dot gain compensated input image printed on coated paper. As seen in Fig. 6, I_s and I_m are compared to check whether the difference in the convergence of their intensities lies within the range of a predetermined threshold, Th. The criterion for deciding on the convergence of two intensities is as follows.

$$f(I_s, I_m) < \mathrm{Th} = \left\{ \frac{|I_s - I_m|}{I_s} < \mathrm{Th} \text{ or } c < 20 \right\} \tag{8}$$

where C is the maximum iteration number. If the difference between I_s and I_m is larger than Th, the primaries for the match should be compensated. This process compensates the digital inking values of the match by multiplying a scale factor with the CMY components of the match. If the difference does not converge in the first comparison for the two intensities, the range of the scale factor is divided into two regions. If I_s is higher than I_m, the amounts of the CMY components for the match are reduced to brighten the match-image. Otherwise, the CMY components for the match are increased. In our experiment, x was fixed as the normalized-initial-intensity-difference(NIID), $|I_s - I_m| / I_s$. Accordingly, in the case of $I_s > I_m$, the first lower range of the scale factor is from 1 - NIID, the lower boundary of the first lower range to 1, and the upper bound of the first lower range. Otherwise, the first upper range of the scale factor is from 1, the lower bound of the first upper range to 1 + NHD, the upper bound of the first upper range. After selecting the first range for the scale factor, the ranges are then divided again into two candidate ranges. This generates two interim scale factors i.e., SF_U, the center point of the divided upper region, and SF_L, the center point of the divided lower region. Thereafter, the primaries used for the match are compensated by multiplying these two scale factors.

This compensation process produces I_{mu} and I_{ml} which are two new average intensities for the match. Next, when I_{mu} and I_{ml} are compared with the intensity of the sample, the region of a candidate scale factor which has the least intensity difference with the sample is chosen as the next candidate region. In Fig. 7, a graphical description of the range division of a scale factor has been added.

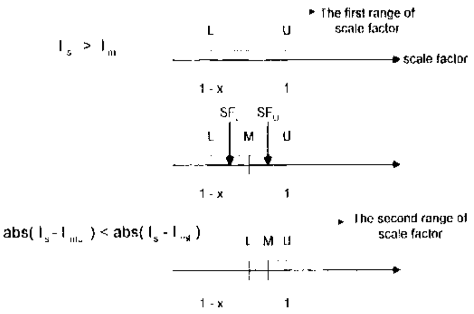


Fig. 7. The graphical description of the range division of a scale factor

This process is repeated in order to identify a scale factor which converges the intensity difference between the sample and the match into Th. Fig. 8 presents a block diagram for color printing including the dot gain compensation and the intensity matching.

6. EXPERIMENT

In an experiment using the proposed algorithm, HP-560K and HP-660K printers were used for printing. As substrate materials, HP-C3837A is used for glossy paper and Hansol-51360Z for coated paper. For a comparison of the dynamic ranges of saturation for color spaces, color charts of two substrates were printed at 300dpi and 600dpi. The input images of RGB format were transformed into an image of CMY components for printing using a simple equation where $C = 1 - R$, $M = 1 - G$, and $Y = 1 - B$. To compare the output image on the two substrates, 'Peppers' was printed on glossy paper using the order dithering. Next, the proposed compensation algorithms were applied to the input image and the resultant image was printed on coated paper using the same dithering method.

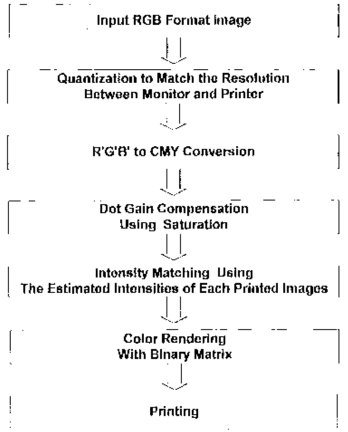
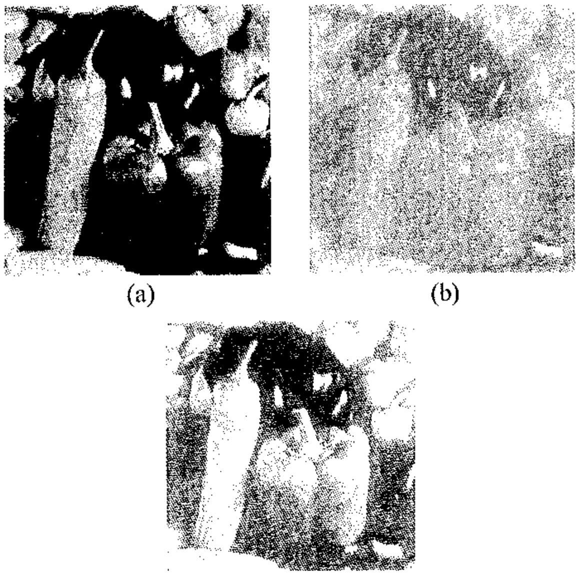


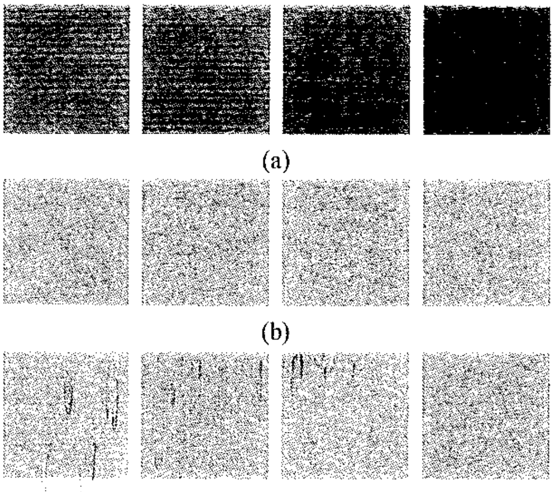
Fig.8. The block diagram of color printing with color matching between different substrates


(a) (b)

(c)

Fig. 9. The printed peppers on glossy paper and coated paper using an ink jet printer (a) Glossy paper (b) Coated paper (c) Coated paper by the proposed color matching algorithm.

In Fig. 9, (a) and (b) are printed the same way. The different substrates resulted in severe color differences between the output images. However, (c) is the resulting image on coated paper when the proposed algorithm is used. (c) is well matched to (a).



(a)

(b)

(c)

Fig. 10. Color chart made with glossy and coated paper (9 ~ 12 [dots /pixel] for CMY) (a) Color patches printed with same amounts of cyan, magenta, and yellow on glossy paper (b) Color patches printed with same amounts of cyan, magenta, and yellow on coated paper (c) Color patches printed with the proposed color matching algorithm on coated paper.

Fig. 10 illustrates the color patches made on glossy and coated paper. As in the experiment using the 'pepper' image, (c) is visually well matched to (a). According to the colorimetric approach, the color difference values in the CIELAB are shown in Table 2. In this case, the equation to identify the color difference is as follows.

$$\Delta E_{ab} = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \qquad (9)$$

Table 2. The CIELAB values and color differences in CIELAB color space (a) 9[dots/pixel] for CMY (b) 10[dots/pixel] for CMY (c) 11[dots/pixel] for CMY (d) 12[dots/pixel] for CMY

※ Sample: Fig.10. (a) Match: Fig.10. (b) Compensated match: Fig. 10. (c)

	L	a	b	△Eab
Sample	46.68	16.20	-24.42	-
Match	51.16	4.22	-17.42	13.86
Compensated Match	50. 63	19.42	-32.30	5.41

(a)

	L	a	b	△Eab
Sample	46.24	15.56	-25.42	-
Match	50.49	4.06	-18.96	13.86
Compensated Match	50.86	13.82	-27.63	5.41

(b)

	L	a	b	△Eab
Sample	41.33	18.14	-26.83	-
Match	49.22	4.23	-18.04	18.25
Compensated Match	50.15	13.62	-28.24	10.01

(c)

	L	a	b	△Eab
Sample	36.79	21.35	-30.71	-
Match	51.37	4.60	-15.32	27.02
Compensated Match	47.93	15.27	-26.04	13.52

(d)

In addtion, when compared with the color difference in uniform color space, color charts (c) in Fig. 10 printed by the proposed compensation algorithm produced much less color difference than the color charts shown in (b) in Fig. 10.

7. CONCLUSION

The proposed color matching algorithms have been developed in the pursuit of substrate-independent color reproduction in the area of device-independent color reproduction. To obtain independent color on a substrate, the dot gain of a substrate was predicted and compensated using the saturation of color patches. These color patches indicated the full range of saturation in relation to the amounts of each primary ink.

After the dot gain compensation, intensity compensation was introduced, which matched the intensity between two resultant images on glossy and coated paper. To demonstrate the effectiveness of the proposed color matching algorithm, a real image and artificial color charts were used.

As a result, both resulting images visually and numerically were well matched to the glossy paper. However, the colors in the highlight region of output image on coated paper were coarser than the corresponding colors of same position on glossy paper. It would seem that there was an overcompensation for the small CMY components, therefore, further research is needed for adaptive compensation for the quantization level of CMY components levels.

ACKNOWLEDGMENT

This research was supported by KOSEF-RRC under contract number 98-09-07-01-B-1.

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BIOGRAPHIES

Cheol-Hee Lee received his B. S. and M. S. in Electronic Engineering from Kyungpook National University, Taegu, Korea, in 1995 and 1997, respectively. Currently, he is studying toward Ph. D. in School of Electronic and Electrical Engineering from Kyungpook National University. His main research fields are in color image processing, color reproduction, and neural network.

Chae-Soo Lee received his B. S. and M. S. in Electronic Engineering from Kyungpook National University, Taegu, Korea, in 1994 and 1996, respectively. In March 1999, he joined the Department of Computer Information Engineering of Kyungwoon University. His main research fields are in color image processing, color printing, and gamut mapping.

Yeong-Ho Ha received the B. S. and M. S. degrees in Electronics Engineering from Kyungpook National University, Taegu, Korea, in 1976 and 1978, respectively, and Ph. D. degree in Electrical and Computer Engineering from the University of Texas at Austin, Texas, 1985. In March 1986, he joined the Department of Electronic Engineering of Kyungpook National University, as an Assistant Professor, and is currently a Professor. He served as TPC co-chair of 1994 IEEE International Conference on Intelligent Signal Processing and Communication Systems and he is now chairman of IEEE Taegu section. His main research interests are in image processing, computer vision, and video signal processing. He is a member of IEEE, Pattern Recognition Society, IS&T, Institute of Electronics Engineers of Korea and Korean Institute of Communication Sciences.