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User-Configured Monitor-to-Printer Color Reproduction

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Abstract. *Every type of color imaging device has its own color reproduction method, providing color characteristic information. Thus, a color management system with an ICC profile is generally used to reproduce colors between two different color imaging devices, for example, from a monitor to a printer. However, once the ICC profile of a device is measured and stored, it usually remains unchanged. Yet, a user can sometimes control the monitor configuration, such as the color temperature, contrast, and brightness, according to their preference, thereby changing the color characteristics of the monitor. In addition, typical end user's viewing condition is not matched to standard environment. In this case, if the user then prints an image on the monitor screen, the color of the printed image will not match the color displayed on the monitor screen, as the color characteristics of the ICC profile provided by the monitor manufacturer will no longer represent the user-configured color characteristics of the monitor. Therefore, this article proposes a method for user-configured monitor-to-printer color reproduction based on an estimation of the monitor characteristics under user's monitor configuration and viewing condition. First, the color characteristics according to change of monitor configuration is measured and modeled for the red-green-blue (RGB) chromaticity and tone curve. Second, to estimate the color characteristics of the user's monitor, color matching between a printed color chart and a reproduced color chart image on the monitor screen by soft proofing is accomplished. The RGB chromaticity and tone curve models are used in a soft proofing process for adjusting the monitor's color characteristics. After color matching, color characteristics of the user's monitor are then obtained. Finally, the monitor to printer color reproduction is evaluated based on the color characteristics obtained for the monitor. Experimental results using the proposed method show that the printed images have almost the same colors as the images on the real user-configured monitor screen.* © *2011 Society for Imaging Science and Technology.*
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INTRODUCTION

As every type of color imaging device has its own materials and method for reproducing color, such as a red-green-blue (RGB) color filter and backlight unit in a liquid crystal display (LCD) monitor, CMYK inks and halftoning in a printer, and RGB color filter and charge-coupled device array in a digital camera, this results in a different color gamut or range of reproduced colors for each device. Thus, color characterization and gamut mapping processes are needed to reproduce colors from one device to another, and these processes form the core of general color management systems for color reproduction.[1,2]

A device independent color space, such as CIEXYZ or CIELAB color space based on the human visual system, is generally used in color management systems, where the color is the stimulus perceived by the human eye. To estimate the relation between a device color space and a device independent color space, the device color space is sampled and the sample colors measured using a spectrometer, resulting in CIEXYZ values for each sample color. Using these sample data, a device characterization model or three-dimensional conversion lookup table is then generated that allows the color values of the device color space to be converted into device independent color space and vice versa. In the case of displays such as cathode-ray tubes, LCD, plasma display panel, and projectors, the gain offset gamma (GOG) and S-curve model are used to estimate an optoelectronic transfer function for the linearization of each RGB channel. Thereafter, the tristimulus values, CIEXYZ or CIELAB, are estimated through a linear transformation using a matrix.[3–7]

After the conversion process from a device dependent color space to device independent color space, color data from two devices can be mapped using gamut mapping algorithms based on compression and clipping methods. The goal of gamut mapping is improved color reproduction, which needs to be evaluated by the human eye without reference. As the results of a gamut mapping algorithm depend on the type of image, various gamut mapping algorithms have already been developed, and it remains an area of active research. Therefore, constructing a user-friendly color reproduction system is hard due to inconsistent characterization and the diversity of gamut mapping algorithms.[8,9]

The International Color Consortium (ICC) already defined a device profile format, an ICC profile, for the color characteristic information of a device, which has since been adopted as an international standard for color management systems. As such, an ICC profile includes the primary colors of a device, sample color data, and tone curve information for each channel, facilitating the easy conversion of arbitrary device colors into a profile connection space, CIELAB or

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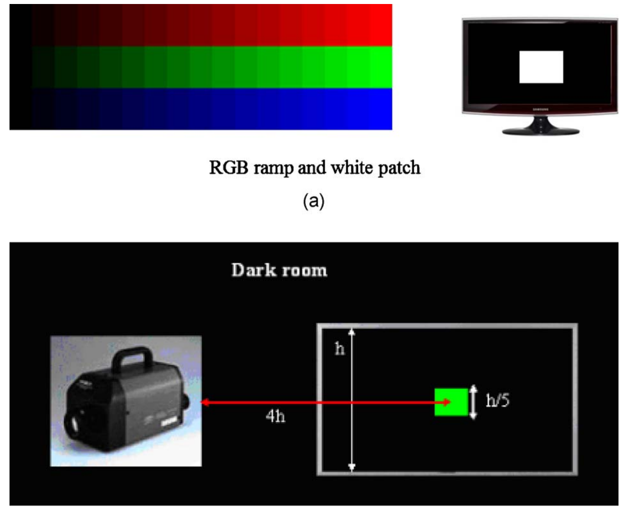
CIEXYZ, and vice versa. Plus, the gamut mapping can be specified using tables, to which interpolation is applied. Consequently, most color imaging devices use a color management system with an ICC profile.[10]

However, the color information included in an ICC profile for a color management system is generally obtained and stored based on measurements taken during the development process, making it relevant to the initial condition of the color imaging device at the factory, yet not the real condition of the color imaging device in use. The color characteristics of a color imaging device in use are different to the initial color characteristics of the color imaging device, especially in the case of a display device with a lamp. The lifetime of a lamp is limited and its performance continuously decreases, thereby inducing a color shift for the display. Thus, monitor calibration with a measuring tool is necessary according to the used time to maintain the color accurately, and this is a challenge for the end user. Moreover, when adjusting the configuration of a monitor, the color characteristics is changed. The color temperature, contrast, and brightness are all basic configuration factors, plus various color rendering modes according to the user's taste have recently been added to monitors, such as text, picture, movie, and Adobe RGB modes. Consequently, as the initial color characteristics of a monitor determined at the factory are invariably not preserved, any color matching between the monitor and a printer will exhibit a significant color difference unless the monitor ICC profile is corrected.[11,12]

Accordingly, this article proposes a method for estimating the color characteristics of a monitor based on considering a user-controlled monitor configuration to enable monitor-to-printer color reproduction. The variation of the monitor characteristics is first modeled by measuring each configuration for various monitors. Thus, the monitor profile adjusted by the proposed color matching process is different to the ICC profile obtained under a standard illuminant, as it can only be used under specific viewing conditions. However, it allows the reproduction of the colors perceived by the user, as the profile considers the viewing conditions of the user. Therefore, the soft proofing process is performed under general office conditions. The monitor ICC profile is iteratively modified using the estimated monitor characteristic model until the color matching is completed. Finally, the modified monitor ICC profile is used for the monitor-to-printer color reproduction process.

MONITOR COLOR CHARACTERISTICS

The standard color space for monitors is usually sRGB color space. The chromaticity values for the RGB primaries are fixed and the tone curves for each channel are determined using a gamma curve model, except for the linear part for the low digital values. The white point is also determined by the white chromaticity of the standard illuminant, D65.[8] If the color of a monitor is precisely produced, as in the case of no change in the specifications and monitor color characteristics, there will be no problem matching the color between the monitor and a printer, except for the color difference from the gamut difference. However, since the brightness and chromaticity of the backlight unit in a monitor decrease and change, this induces a different monitor characteristic to sRGB color space. Thus, to analyze the color characteristic of a real monitor, the RGB ramp and white patch for various monitors are measured in a dark room, as shown in Figure 1(a). The chromaticity values for the RGB primaries and tone curve are obtained from the measured data of the ramp. Meanwhile, the chromaticity of white is obtained from the measured white patch. The measurement of each patch is accomplished using a spectrophotometer under standard conditions, as shown in Fig. 1(b). Thirty LCD monitors produced in 2003–2009 were used for the measurement. Although the time in use and models are all different from each other, the initial configuration of the monitors is the same initial mode.



(a)

(b)

Figure 1. (a) RGB ramp and white patch and (b) environment for measurement.

Figure 2(a) shows the RGB primaries at maximum intensity and white chromaticity values of the monitors in CIEXY color space. Most of the RGB primaries at maximum intensity, except for white, were close to the chromaticity values for the respective primaries in sRGB color space. Meanwhile, the chromaticity values for comparing the white patches are distributed along a curve of the correlated color temperature in Fig. 2(b). While many of the monitors were close to 6500 and 6000 K, the white chromaticity values for the older monitors were shifted toward a lower temperature. Some of the monitors even had a higher color temperature than 6500 K. The difference between the white chromaticity values and the sRGB color space values for the monitors depended on the time in use. Thus, a monitor needs to be measured to obtain the exact and real chromaticity value. In the case of the tone curve for each RGB channel, they were slightly different from the gamma curve of sRGB color space, as shown in Figure 3. The fact that LCDs show an S-shaped tone response curve is widely known. Yet, most of the LCD monitors, except for two among 30, showed a gamma curve. The average gamma values were 2.47, 2.39,

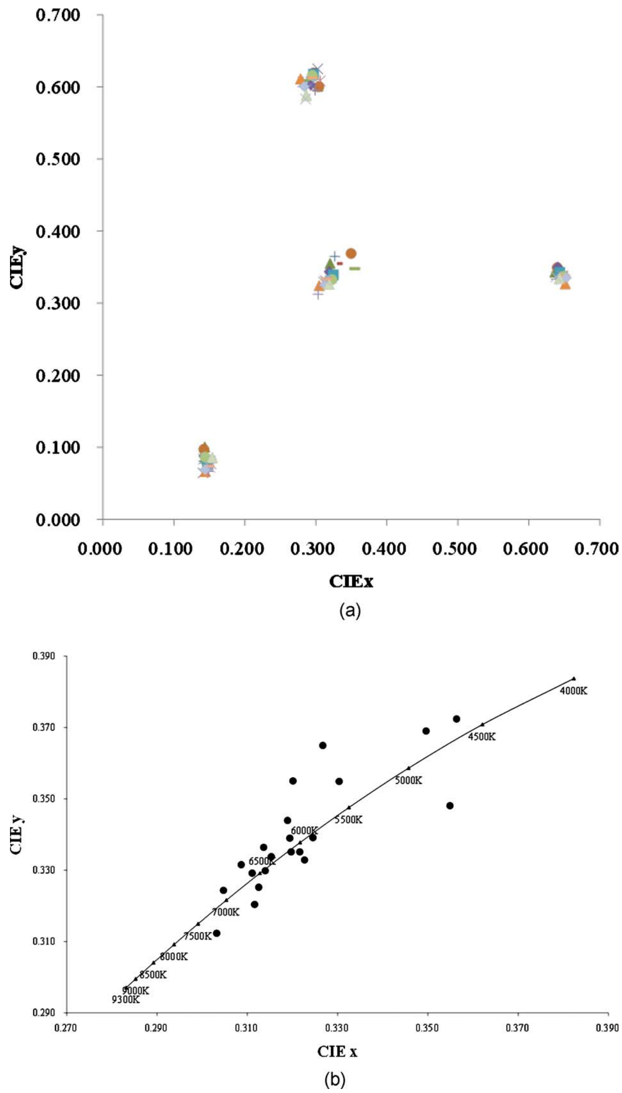


Figure 2. (a) Chromaticity values for RGB primary at maximum intensity and white patch in CIEXY color space and (b) chromaticity values of white patch comparing the curve of correlated color temperature.

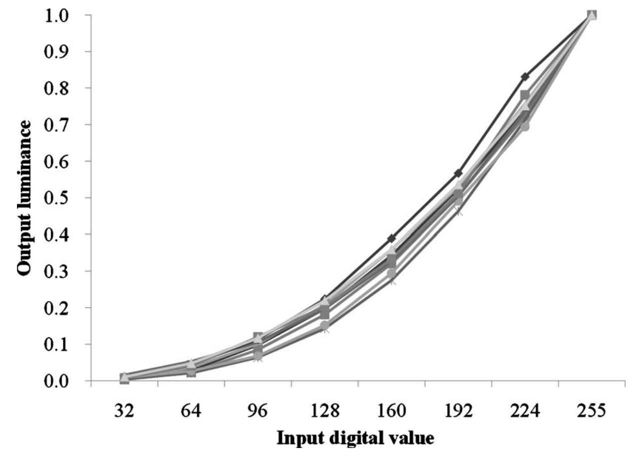


Figure 3. Tone curves of green channel for various monitors.

and 2.15 for the RGB channels, respectively. Thus, the gamma values for the red and green channels were higher than the 2.2 gamma value for sRGB, whereas the gamma value for the blue channel was lower. Therefore, the color characteristics of the monitors in use differed from standard sRGB color space even when the monitor configuration mode was the sRGB mode. Thus, the GOG model will be used to correct the tone curve characteristic in the later soft proofing process.

These differences in the monitor color characteristics are caused by the model, time in use, and monitor configuration. Plus, the differences in the materials used and driving method for each model induce a different performance in color reproduction. In the case of the same model, the brightness and chromaticity of the backlight change according to the time in use. Moreover, the monitor configuration, such as the color temperature, contrast, and brightness, can artificially change the color characteristic.

It is hard to estimate the changes of the monitor characteristics due to material characteristics, the environment, and time used. However, the change due to the monitor configuration is easy to control when compared with other changes. Thus, the monitor characteristic model used in the soft proofing process is determined based on the change due to the monitor configuration, and it is assumed that this model can also be used to estimate other changes. Therefore, this study focused on the color characteristic changes due to the monitor configuration.

COLOR TEMPERATURE

The color temperature of a monitor is an important factor for evaluating the image quality performance of a monitor, as it is related to the sensitivity of the human visual system, such as warmness and coolness. Thus, most monitors have a configuration for the color temperature, which influences the chromaticity of white in the characteristics of a monitor. As shown in Figure 4, when changing the configuration of the color temperature from 6500 to 9300 or 5000 K, the chromaticity values for the RGB primaries remained almost fixed, yet the chromaticity value of white shifted in the opposite direction for each configuration. While the color filter or phosphor of a monitor cannot be changed, thereby fixing the chromaticity of the RGB primaries, the intensity of the RGB primaries is controllable, meaning that the chromaticity of white can be changed by the intensity ratio of the RGB primaries. This characteristic of a monitor can be represented as follows:

$$\mathbf{P}_k = g_k \mathbf{Q}_k, \tag{1}$$

where $\mathbf{P}$ is the estimated CIEXYZ value, $\mathbf{Q}$ is the initial CIEXYZ value, g is the gain for a change in the intensity of a RGB primary, and k indicates the index for the CIEXYZ value. To maintain the chromaticity of each primary, the same gain value is applied for each CIEXYZ. The equation can also be put into a matrix form,

$$\begin{bmatrix} X_R^{est} & Y_R^{est} & Z_R^{est} \\ X_G^{est} & Y_G^{est} & Z_G^{est} \\ X_B^{est} & Y_B^{est} & Z_B^{est} \end{bmatrix} = \begin{bmatrix} g_R & 0 & 0 \\ 0 & g_G & 0 \\ 0 & 0 & g_B \end{bmatrix} \begin{bmatrix} X_R^{ini} & Y_R^{ini} & Z_R^{ini} \\ X_G^{init} & Y_G^{init} & Z_G^{init} \\ X_B^{init} & Y_B^{init} & Z_B^{init} \end{bmatrix}. \tag{2}$$

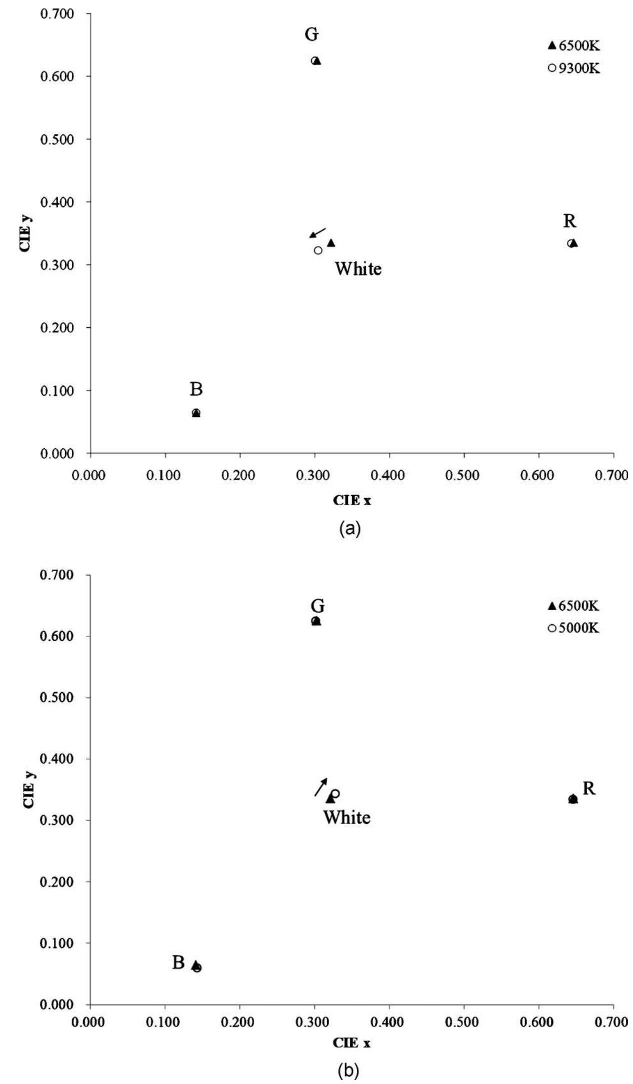


Figure 4. Chromaticity of RGB and white varying configuration for color temperature from 6500 K to (a) 9300 K and (b) 5000 K.

When varying the configuration of the color temperature, the gains for each RGB primary can be estimated by measuring the RGB primaries for a monitor using the following equation:

$$\begin{bmatrix} g_R & 0 & 0 \\ 0 & g_G & 0 \\ 0 & 0 & g_B \end{bmatrix} = \begin{bmatrix} X_R^{mea} & Y_R^{mea} & Z_R^{mea} \\ X_G^{mea} & Y_G^{mea} & Z_G^{mea} \\ X_B^{mea} & Y_B^{mea} & Z_B^{mea} \end{bmatrix}^{-1} \begin{bmatrix} X_R^{ini} & Y_R^{ini} & Z_R^{ini} \\ X_G^{init} & Y_G^{init} & Z_G^{init} \\ X_B^{init} & Y_B^{init} & Z_B^{init} \end{bmatrix}. \tag{3}$$

The RGB gains are estimated using the measured *XYZ* values for the RGB primaries and initial *XYZ* values, for example, the *XYZ* values for the RGB primaries in sRGB color space or in the monitor ICC profile.

CONTRAST AND BRIGHTNESS

The configuration for contrast and brightness is related to the tone curve for each RGB channel. Generally, the range of contrast or brightness is from 0 to 100, and the default value is set at 70 or 80. Figure 5(a) represents the tone curves of the green channel for maximum contrast. In contrast with Fig. 3, the slope of the tone curve is increased, thereby clipping the tone curve with a high input level. An increase in the configuration value for the contrast changes the slope and maximum value of the tone curve, as a shown in Fig. 5(b). As the maximum luminance values of color imaging devices differ from each other, color matching between color imaging devices is performed in a relative color space, CIELAB. The luminance of each color imaging device is scaled 0–1 or 100. Thus, after normalizing these values with the maximum value, the tone curves corresponding to below the default value for the contrast become the same as the tone curve for the default value, and the slope of the other tone curves is increased in proportion to the change of contrast, as shown in Figure 6. This means that the contrast value of the monitor configuration is related to the slope of the tone curve and a decrease in the contrast value has no further influence beyond a certain contrast. As a result, the change of the tone curve according to the contrast value can be estimated based on the change of the slope.

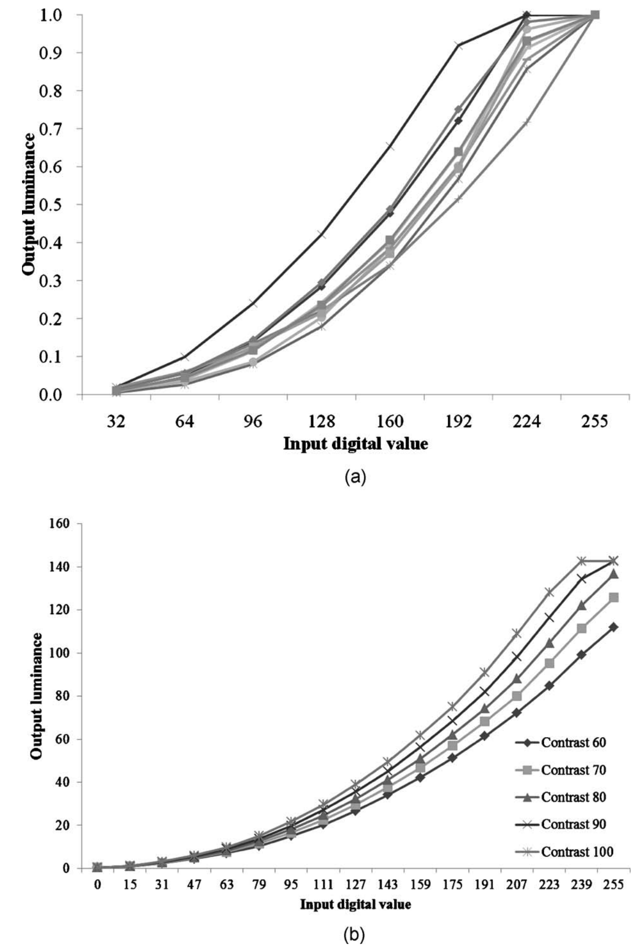


Figure 5. Tone curves for each configuration, (a) maximum contrast, (b) varying contrast, (c) normalized curves varying contrast, and (d) varying brightness.

The tone curves resulting from a change of the configuration for brightness are represented in Figure 7. Although the absolute maximum values for each tone curve are

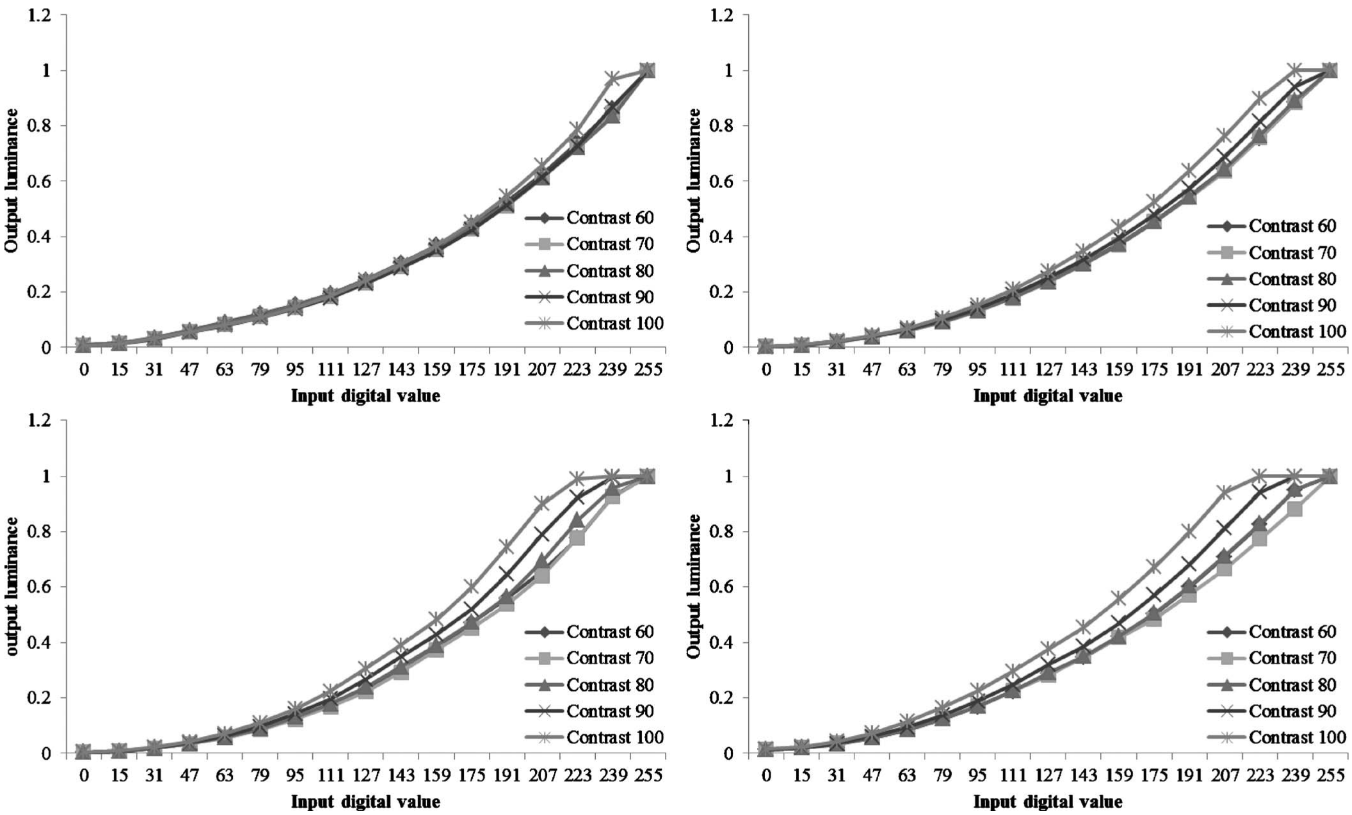


Figure 6. Change of normalized tone curves varying contrast of configuration for four monitors.

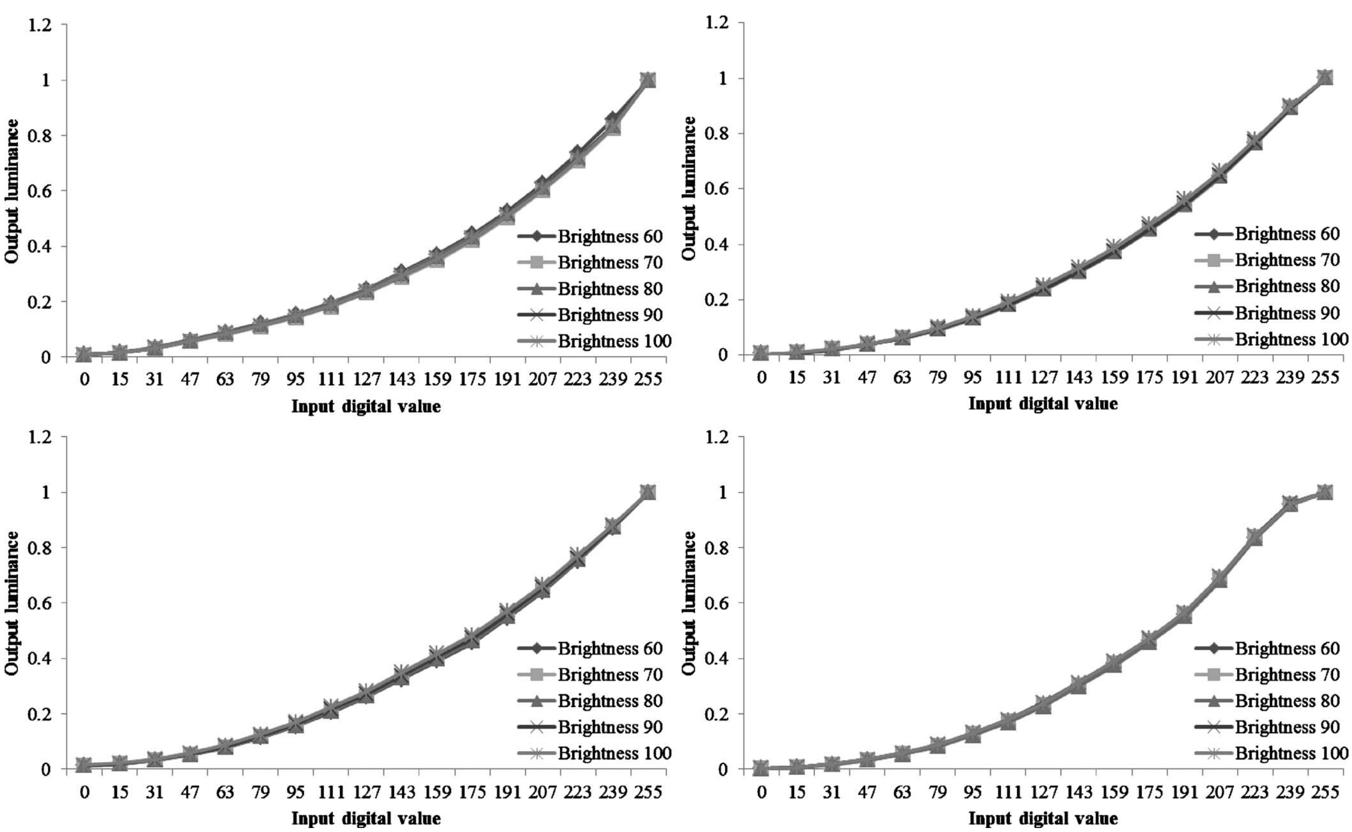


Figure 7. Change of normalized tone curves varying brightness of configuration for four monitors.

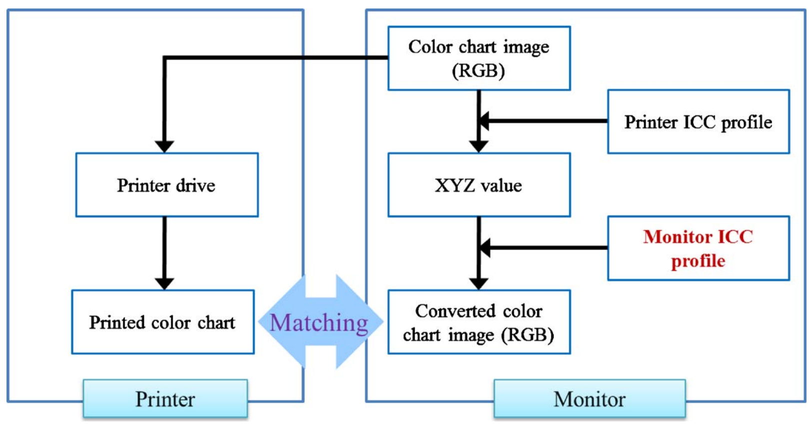


Figure 8. Estimation of monitor ICC profile using color matching by soft proofing.

different, these curves become almost same after normalizing with each maximum value. A change in the brightness configuration does not influence the color reproduction. As a result, the change of the tone curve is related to contrast configuration values. The change of the tone curve when varying the contrast configuration can be estimated by the gain in a general GOG model using the following equation:[13,14]

$$Y_i = \left[k_{g,i} \left(\frac{d_i}{2^N - 1} \right) + k_{o,i} \right]^{r_i}, \tag{4}$$

where d represents the input digital value for each channel, N is the number of bits for the input data, and k_g, k_o, and γ are the parameters for the gain, offset, and gamma; k_g is related to the slope of the curve, which is modified according to the variation of the contrast configuration when fixing k_o and γ to zero, allowing the average gamma value to be measured for various monitors. In addition, a few curves are similar to an S curve. Yet, the shape of the curve comes from the shape of the gamma curve based on an analysis of the measured tone response curve when varying the contrast and brightness configuration of the monitor. Although the characteristic curve of LCDs generally corresponds to an S curve, it is supposed that the manufacturers of LCDs are tending to aim at an optimized gamma in the default value.

COLOR MATCHING

Sample patches on a monitor are measured to estimate the color characteristics of a real monitor exactly. Yet, such measurement tools are expensive and not common for the end user without knowledge of color management systems. The final evaluation of color reproduction between a monitor and a printer is subjectively determined by the user, as the color gamuts are different and the colors outside the gamut cannot be reproduced without a gamut mapping process. Therefore, a method for estimating the monitor characteristic is proposed based on a color matching. Using a printed color chart as the reference image, the color chart on the monitor then becomes the target. The color chart does not mean a standard color chart, such as the Macbeth color checker or Kodak chart. It is only used for color matching, not characterization. As such, the chart only needs to include a sufficient number of colors to reflect the color reproduction intent of the user. By controlling the color characteristic of the monitor, color matching is accomplished under general viewing conditions. The result does not depend on the viewing condition as it does not find the exact color characteristic of the monitor but rather a relative color difference with respect to a reference. To match the reference color of the printed color chart and target color on the monitor, the color of the monitor is adjusted. Finally, the color characteristics of the monitor are estimated using the adjusted color information of the monitor after completing the color matching process.

Figure 8 shows the flow of the color matching. The test chart image on the monitor is represented by a soft proofing process using the printer ICC profile and monitor ICC profile.[15,16] First, the input color chart image is printed and used as the reference in the color matching process. Also, the RGB values for the input color chart image are converted into *XYZ* values using the printer ICC profile. In addition, the printer driver means a direct printing driver, which includes a transformation from RGB to *XYZ* and then to CMYK. Plus, the printer ICC profile is obtained by measuring the printed color chart using the printer driver. Thus, it is the same printing system. These *XYZ* values then represent the *XYZ* values for the printed color chart and are reconverted into RGB values using the monitor ICC profile. Finally, the colors of the converted color chart image on the monitor become the same as the colors of the printed color chart if the ICC profile exactly represents the characteristics of the monitor and printer and the conversion process is more accurate. As such, the conversion processes include device characterization and a gamut mapping process. In addition, the color reproduction performance and stability of the printer were better than those with other color imaging devices as the materials reproducing the colors, the inks, and the headers could be changed to new ones. Thus, it was assumed that the printer ICC profile provided by the manufacturer was accurate, and it was used without any correction process.

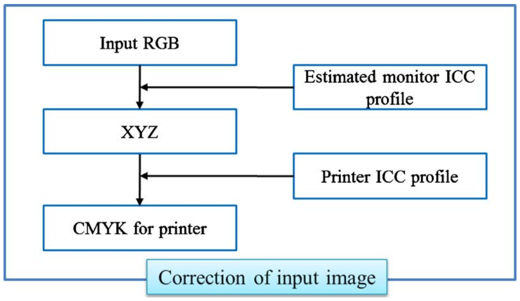


Figure 9. Color conversion process with estimated monitor's ICC profile.

The monitor ICC profile is adjusted for color reproduction using a color matching process, as the monitor ICC profile provided by the manufacturer is not accurate. Due to the large gamut difference between a monitor and a printer, the result of gamut mapping strongly depends on the mapping algorithm and mapping intent. Thus, gamut mapping algorithms based on the ICC profile are applied. The rendering intent is set to an absolute intent. Moreover, we could drive the printing system directly using the ICC profile without any color conversion and tone reproduction by the printer driver as a result of using the direct printing driver supported from manufacturer.

To adjust the color characteristic of a monitor, the monitor ICC profile is modified based on the RGB primary model for varying the color temperature configuration and the tone curve model for varying the contrast configuration, as in Eqs. (2) and (4). RGB gains in color temperature shift model and curve gains for each RGB channel in GOG model are adjusted to match the colors. The range of the two gains is determined by experiments, namely, user control gains based on predetermined levels, thereby modifying the monitor ICC profile with the estimated values based on the RGB primary and tone curve models. The color on the monitor is then changed by a soft proofing process. These processes are repeated until the color matching test is completed.

The modified ICC profile for a real monitor is obtained through color matching. To reproduce the color on the monitor using the printer, the inverse process of the soft proofing is then performed, as shown in Figure 9.

EXPERIMENTAL RESULTS

Experiments were performed using five LCD monitors and a Samsung CLP 620ND printer. To obtain the ICC profile for the printer, the reflectance of sample patches was measured using a GretagMacbeth Spectrolino spectrophotometer, which measured from 400 to 700 nm in ten intervals under a D50 illuminant. The ICC profile of the monitor as defined by the manufacturer was used in comparison with the proposed method.

First, an objective evaluation using 216 test patches was performed for the modified ICC profile. As shown in Figure 10, the color of the monitor for the 216 RGB patches was measured using a spectroradiometer, CS1000. The configuration of the monitor was reset to the initial condition. Meanwhile, the test patches were directly printed, and the color difference between the test patches on the monitor and the printed test patches is computed as follows:[17]

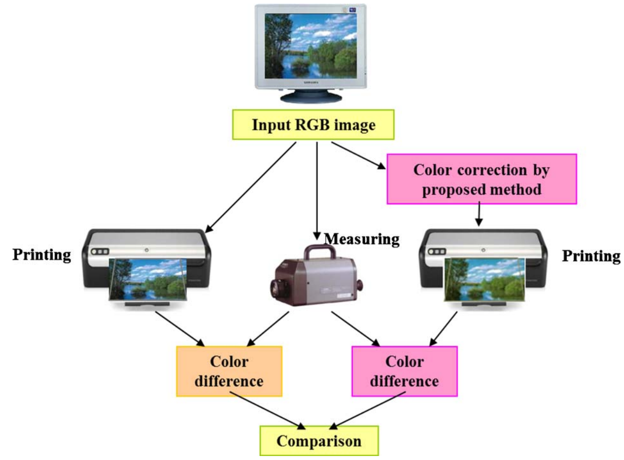


Figure 10. Flow for the quantitative evaluation.

$$\Delta E_{ab} = \sqrt{(L^*_{\text{monitor}} - L^*_{\text{printer}})^2 + (a^*_{\text{monitor}} - a^*_{\text{printer}})^2 + (b^*_{\text{monitor}} - b^*_{\text{printer}})^2}. \quad (5)$$

To change from CIEXYZ to CIELAB color space, reference white D50 was used, as the white points were different for each device. In the case of the monitor, the color space was converted after the XYZ values were normalized using the maximum luminance. This color difference was then used as the criteria for judgment. Thus, it was compared with the printed test patches resulting from the proposed method when estimating the monitor ICC profile using the color matching. The improved results with the proposed method are represented as follows:

$$D = \Delta E_{ab}^{conventional} - \Delta E_{ab}^{proposed}, \quad (6)$$

where D indicates the improvement quantitatively.

Table I shows the evaluation results for the five monitors and printer. The color difference was larger than that with other color reproduction processes, as the colors of the monitor and printer were directly compared and the gamut difference of the two devices is reflected in the color difference. Thus, the 216 RGB patches were separated considering their location in CIELAB color space. The 216 RGB values were converted to CIELAB color space based on the monitor characterization. The patches were then divided into patches inside the printer gamut and outside the gamut. The color difference for the patches inside the gamut was smaller than that for the patches outside the gamut, as the latter included the gamut difference. Figure 11 shows the color difference for all the patches on the EIZO L568 monitor. The distribution of the color differences was similar for the patches with a higher color difference, yet, for some of the patches with a lower color difference, the color differences were reduced by the proposed method.

As a result, the color difference with the proposed method was smaller than that with the default method, indicating that the color of the printed test patches when using

Table I. Color difference between colors of test patches on the monitor and printed test patches.

	Color difference				Difference (*D*)	
	In gamut		Out of gamut			
Monitor No.	Default	Proposed	Default	Proposed	In gamut	Out of gamut
EIZO L568	13.62	9.52	38.05	35.45	4.11	2.60
LG L1720P	15.08	11.19	36.55	31.51	3.89	5.05
Sony SDM-HS74P	15.30	9.71	33.92	29.39	5.59	4.53
Samsung T220G	13.57	10.18	42.13	38.98	3.38	3.16
Samsung CX701N	13.35	11.91	48.80	48.14	1.44	0.45

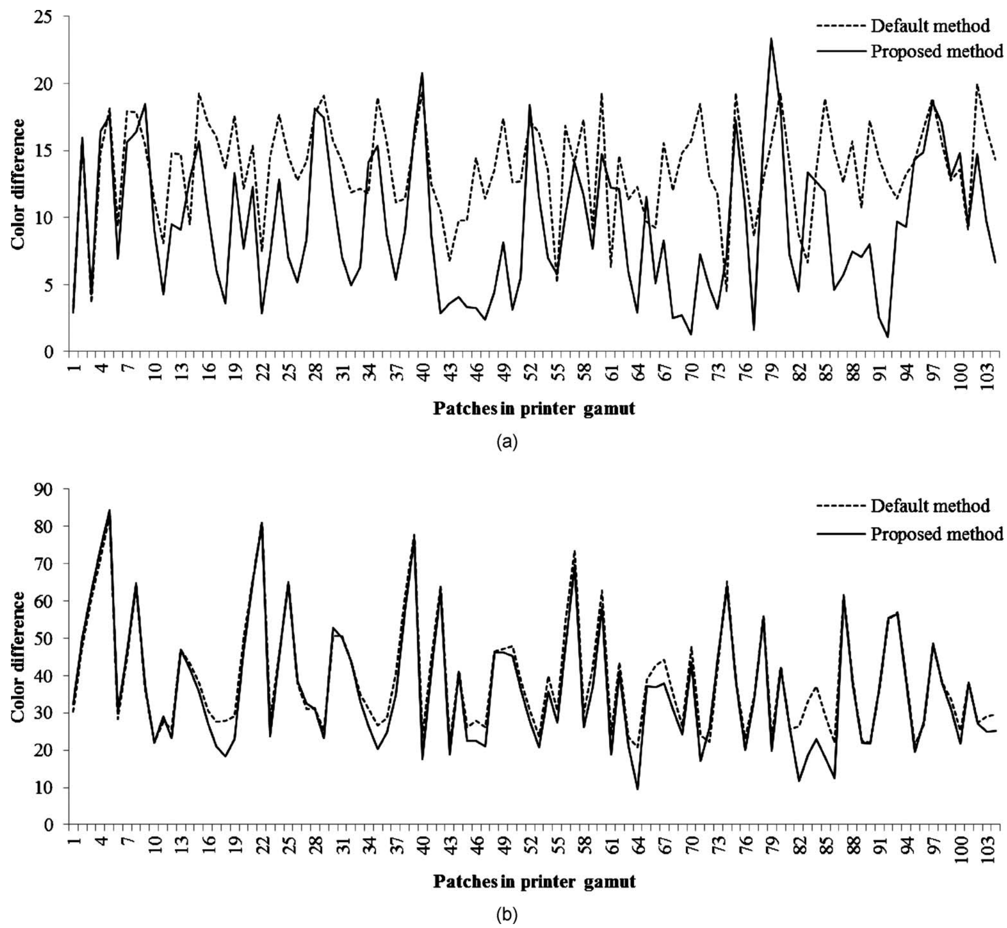


Figure 11. Color difference for (a) in and (b) out of printer gamut patches.

the proposed method was closer to that of the test patches on the real monitor. The printed color is generally influenced by the color of the paper. Although the measurement was accomplished with a measuring tool based on paper white; in the color matching process with soft proofing, the user or tester is more likely to use the color chart image printed on regular paper. In this study, the color of the paper was slightly bluish, namely, it had a higher color temperature than 6500 K. Therefore, if the white color of the monitor is similar to the color of the paper, the difference between the results of the default method and the proposed method would be reduced.

Figures 12 and 13 presents the results obtained when applying the proposed method to real images. For a subjective comparison, the images on the monitor and printed images were captured using a Canon 10D digital camera. The digital camera was set in the manual mode, while the shutter speed and exposure were fixed. A Samsung T220G LCD monitor and CLP 620ND printer were used. The configuration of the monitor was set to the initial condition. Fig. 12(a) shows the captured image of the input image on the monitor. Overall, the white point of the monitor was shifted to a yellowish color. It also exhibited a slight difference with the color characteristic of sRGB color space, especially the

Figure 12. (a) Captured "party" image on the monitor, (b) printed image by direct printer driver, and (c) converted and printed image.

white point. In contrast, Fig. 12(b) shows the captured image for the printed image without any correction. The gray tone of the background is more bluish than that in Fig. 12(a) and especially the skin color is very different. Fig. 12(c) shows the captured image for the printed image when using the proposed method. Here, the gray color of the background is recovered as the monitor's gray color. Plus, the skin color is also closer to the monitor's color. Fig. 13 shows the result for another real image. The captured image [Fig. 13(a)] of the image on the monitor has a higher saturation compared to the printed image using the default method [Fig. 13(b)] because the reddish and yellowish colors of the objects in the image are dominant. Meanwhile, for the image using the proposed method [Fig. 13(c)], the saturation is compensated and the white point is shifted to a yellowish color.

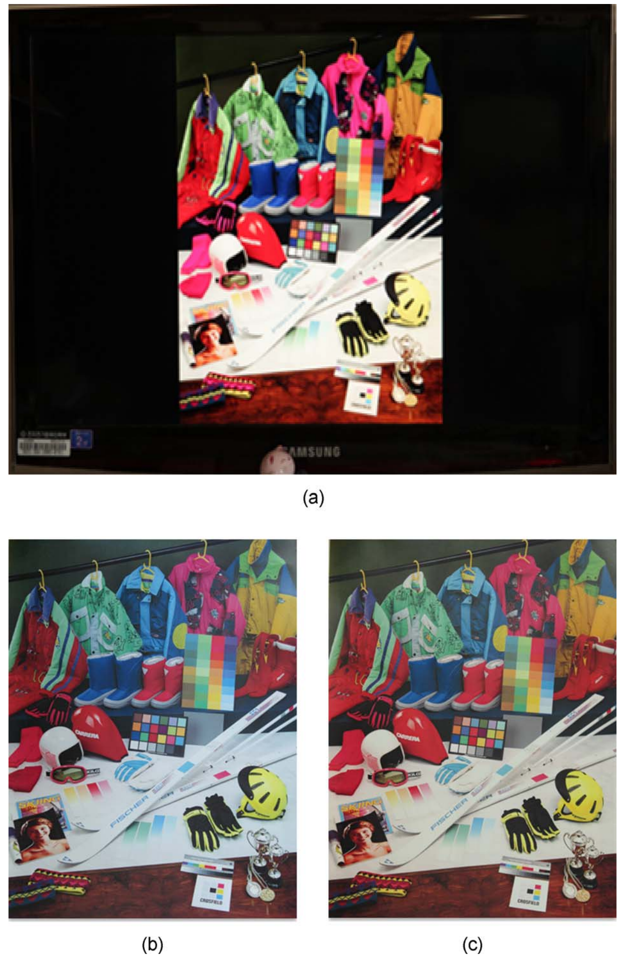


Figure 13. (a) Captured "ski" image on the monitor, (b) printed image by direct printer driver, and (c) converted and printed image.

CONCLUSIONS

Research on reproducing the color on a monitor using a printer remains a consistent focus. Various device characterization methods and gamut mapping algorithms have already been proposed, yet, if these methods use the data measured when the devices were originally manufactured, the difference with the real color of the device is increased. The color characteristic of a LCD monitor changes over time, as it generally uses a cold cathode fluorescent lamp in the black light unit. Thus, color reproduction using the ICC profile provided by the device company is not accurate. Therefore, this article proposed a monitor-to-printer color reproduction method using color matching. In color matching using a soft proofing process, the color of the reproduced image on the monitor is adjusted by the observer using a shift model of the color temperature and the RGB gain parameters of the GOG model based on a monitor analysis until completing the color matching. After color matching between the printed image and the image on the monitor, the relative color characteristics of the real monitor are estimated, and these characteristics are then reflected in the monitor ICC profile. Thereafter, the modified ICC profile is used for the color reproduction process using the printer ICC profile. Even though the modified ICC profile is not the regular ICC profile based on measurement, it reflects the relative color characteristics for the printer used. Therefore, it can reproduce the colors of the monitor through the printer. In the experiments, the colors of the resulting image when using the proposed method had a lower color difference than those when using the default printing process. Moreover, in the image experiments, the results with the proposed method were closer to the image on the monitor than the results with the default process.

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