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Projector-based color simulator for print industry

Shoji Yamamoto†, *non-membership*, Kumiko Ueda†, *non-membership*, Norimichi Tsumura†, *membership*, Toshiya Nakaguchi†, *membership*, and Yoichi Miyake††, *membership*

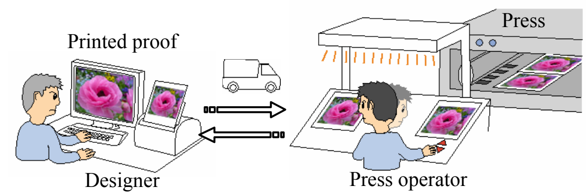
Summary
In this paper, we propose a new projector-based display which can perform the color simulator for print industry. The proposed color simulator can change the color of print by projecting the image onto the print. A color of print can be matched to the desired color by projecting the image which is calculated to minimize the color difference between the colors of target print and current print. This current print is measured by digital camera or digital scanner. Ideally, spectral camera or scanner is expected to be used for accurate color simulation on the current print, but it costs a lot for practical application. Therefore, in this paper, we compared two methods for color matching, one is the tristimulus-based method with XYZ tristimulus values and the other is the spectral-based method with spectral values. As the result of computer simulation, the average color difference ΔE^*_{94} was 0.27 by the spectral-based method between the reflected radiance from the color of target print and the color of current print with projector, and the average color difference ΔE^*_{94} was 2.09 by the tristimulus-based method. The efficiency of the proposed system is verified by the subjective evaluation between the target and current print with appropriate image projection.

Key words:
Digital color proof, Color simulator, Projector, Spectral-based

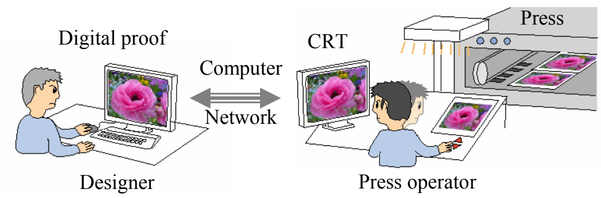
1. Introduction

In the printing industry, digital color proofs have been widely used to design and reproduce the printed matter instead of a conventional color proofs which are printed on paper. The conventional color proof was necessary to be printed and transported iteratively between the designer and the print company for each revision as shown in Figure 1(a). The digital color proof is useful for reducing the cost of transportation and saving the time by using the computer network as shown in Figure 1(b) [1],[2]. Usually, the digital color proof is displayed on the CRT or LCD and compared with a current print in the process of color printing [3],[4]. However, it is not easy to match the color between the hardcopy and digital color proof on the conventional display due to the difference of visual mode in observing the color.

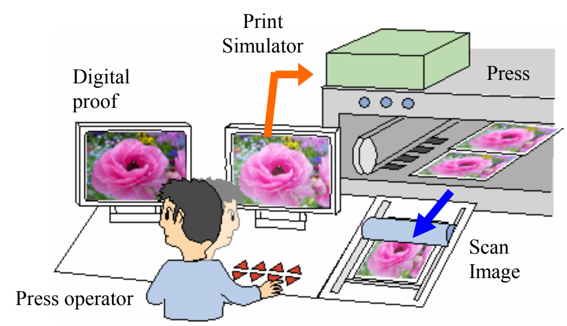
To overcome this difference of visual mode, we have already proposed a high accurate color display system with an image projector [5]-[7]. In this system, the digital color proof is reproduced as the projection image on a white paper, and the current printed paper is illuminated by the projector. For the practical color control, the press operator can observe only diffuse reflected light where they control the printed color by adjusting the ink amount. Therefore, specular reflected light is excluded by devising the mount position of projector as shown in Figures 2 and 3. The color of the digital proof should be calibrated to match the colors between the designer's side and the print company's side. In this system, the visual modes are matched each other between the projected image and the current print illuminated by projector.



(a) Conventional color matching by using the printed proof



(b) Current color matching by using the digital color proof



(c) Color matching by using the digital proof and print simulator

Fig. 1 Progress of color matching in printing industry

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† Graduate School of Science and Technology, Chiba University
1-33, Yayoi-cho, Inage-ku, Chiba, 263-8522
†† Research Center Frontier Medical Engineering, Chiba University
1-33, Yayoi-cho, Inage-ku, Chiba, 263-8522

By using our projector-based system, the press operator can compare the current print with the projected digital color proof, and can control the amount of ink to match the color each other. Usually, this control was not completed by single trial. The operator needs to iteratively print the hardcopy with adjustment of ink amount until the colors match each other. In the conventional digital proofing system, print and color simulators are expected to be used to reduce these iterations as shown in Figure 1(c). The print simulator have been developed to predict the color change caused by the ink control, and the predicted color are expected be reproduced on the display as color simulator [8],[9]. These simulators should be also developed for our projector-based system as shown in Figure 2.

In this paper, we propose a new projector-based display which can perform the color simulator as shown in Figure 4. In our system, the color of current print can be changed by projecting an image according to the result of print simulation [10],[11]. To perform this system, it is necessary to calibrate the projector and calculate the projection image onto the current print. The projection image should compensate the difference between the reflected radiance from the current print and target radiance calculated from print simulation. Here, it is noted that the accuracy of color simulator depends on the accuracy of print simulator and accuracy of calculation for projection image. In this paper, we assumed that print simulator gives the accurate results, and we only evaluate the accuracy of calculation for projection image. For this evaluation, we used radiances from target print as the target radiance calculated from print simulation. The accuracy of calibration technique for projector is explained in section 2. The calculation method for projection image onto the current print is explained in section 3. In this calculation, we evaluated two methods, one is the spectral-based method where the reflectance of the current print is measured by spectrophotometer, the other is tristimulus-based method where the reflectance is measured by RGB camera or RGB scanner. In section 4, we compared the two methods for calculation of projection image based on the computer simulation. In section 5, we compared the two methods by practical experiments. Finally, we discuss the advantage and disadvantage of the two method based on the results of computer simulation and practical experiments, and the paper is concluded in section 6.

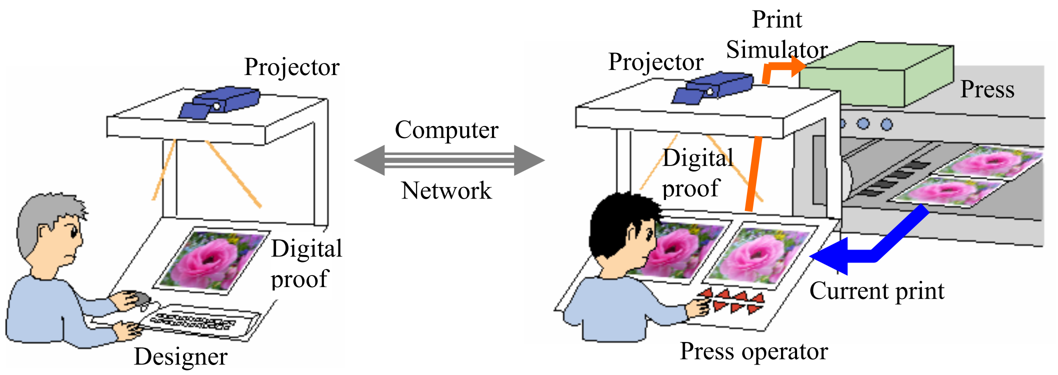

Fig. 2 Schematic illustration of the digital color proofing system with an image projector

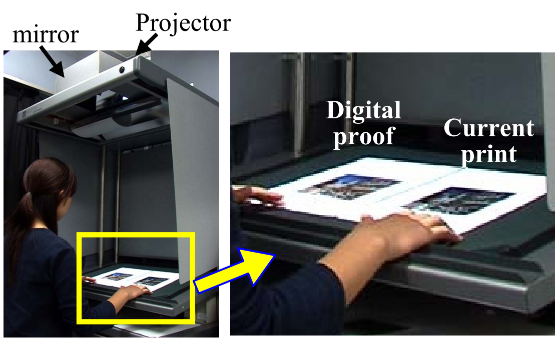

Fig. 3 Projector-based display system

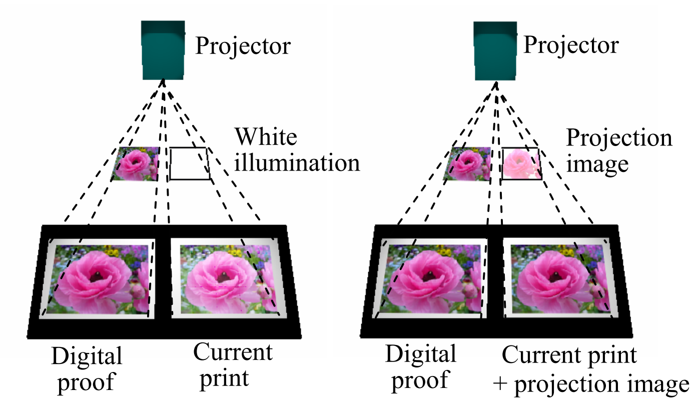

Fig.4. Color simulator for current print by projecting an image

2. Calibration of projector

The calibration of projector is performed to obtain the relationship between the digital counts of projection image and the radiance from the projector. The radiance from the projector can be measured by reflected radiance from the white paper illuminated by the projector. The radiance from LCD projector consists of three primary colors as shown in Figure 6 (i.e. red, green and blue) [12],[13]. In this paper, we used the PCA-Spline model for projector calibration, since this model is effective for three primary colors type of display [14].

In the PCA-Spline model, the relationship between the digital counts and the radiance can be written as Equation 1 in spectral domain,

$$L_i(d_r,d_g,d_b,\lambda)= C_r(d_r)V_r(\lambda)+C_g(d_g)V_g(\lambda)+C_b(d_b)V_b(\lambda)+L_o(\lambda), \quad (1)$$

where d_r,d_g,d_b are input digital 8-bit counts for red, green and blue channels, $V_r(\lambda),V_g(\lambda),V_b(\lambda)$ are basis functions of each primary colors, C_r,C_g,C_b are the coefficients of nonlinear response, $L_0(\lambda)$ is the radiance of projector when digital counts equal to 0. The basis function $V_r(\lambda)$ is the first principal component of the measured radiances $L_i(d_r,0,0,\lambda)$, when digital input d_r is varied from 0 to 255 with an interval of 15. The basis functions $V_g(\lambda)$ and $V_b(\lambda)$ are also obtained by above measurement and calculation. The coefficient C_r,C_g,C_b for the digital count d_r,d_g,d_b can be calculated by using the following equation,

$$\begin{aligned} C_r(d_r)&=\int_{400}^{700}(L_i(d_r,0,0,\lambda)-L_o(\lambda))V_r(\lambda)d\lambda \\ C_g(d_g)&=\int_{400}^{700}(L_i(0,d_g,0,\lambda)-L_o(\lambda))V_g(\lambda)d\lambda \\ C_b(d_b)&=\int_{400}^{700}(L_i(0,0,d_b,\lambda)-L_o(\lambda))V_b(\lambda)d\lambda \end{aligned} \quad . \quad (2)$$

An arbitrary digital input corresponding to C_r,C_g,C_b can be calculated by using spline interpolation as shown in Figure 5.

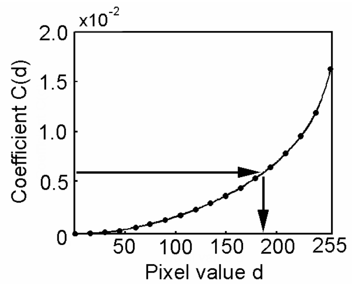

Fig.5 The relationship between pixel value and coefficient

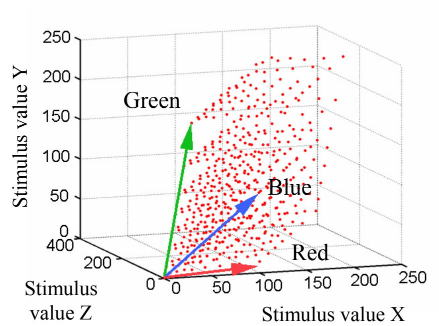

Fig. 6 Radiance of LCD projector corresponding to digital counts

This model in spectral domain can be transformed to the model in the colorimetric domain by using the color matching functions. The XYZ tristimulus values for spectral radiance can be written as Equation 3 in the colorimetric domain.

$$X_i=\int_{400}^{700}L_i(\lambda)\bar{x}(\lambda)d\lambda,\quad Y_i=\int_{400}^{700}L_i(\lambda)\bar{y}(\lambda)d\lambda,\quad Z_i=\int_{400}^{700}L_i(\lambda)\bar{z}(\lambda)d\lambda \quad , \quad (3)$$

where, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ are color matching functions. The relationship between input digital counts and XYZ tristimulus values is written by substituting Equation 1 into Equation 3.

$$\begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix} = \begin{bmatrix} V_{xr} & V_{xg} & V_{xb} \\ V_{yr} & V_{yg} & V_{yb} \\ V_{zr} & V_{zg} & V_{zb} \end{bmatrix} \begin{bmatrix} C_r(d_r) \\ C_g(d_g) \\ C_b(d_b) \end{bmatrix} + \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} , \quad (4)$$

where

$$V_{mn}=\int_{400}^{700}V_n(\lambda)\bar{m}(\lambda)d\lambda \quad (m=x,y,z,\quad n=r,g,b) . \quad (5)$$

The XYZ tristimulus values X_0,Y_0,Z_0 indicate the values where digital counts equal to 0, respectively.

Equations 1 and 4 give the spectral radiance and tristimulus values for digital counts of projection image. Inverse transformation is often necessary in the application of color matching. In the spectral domain, this inverse transformation can be performed only for spectral radiance which can be written by Equation 1. However, the accurate digital counts can not be obtained by the inverse transformation of Equation 1, since target radiances derived from print color matching is the reflected radiance which is not always expressed by the basis functions of projected radiance. On the other hand, in the colorimetric domain, the inverse transformation can derive the digital counts by using the following equation,

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† Graduate School of Science and Technology, Chiba University
1-33, Yayoi-cho, Inage-ku, Chiba, 263-8522
††Research Center Frontier Medical Engineering, Chiba University
1-33, Yayoi-cho, Inage-ku, Chiba, 263-8522

$$\begin{bmatrix} C_r(d_r) \\ C_g(d_g) \\ C_b(d_b) \end{bmatrix} = \begin{bmatrix} V_{xr} & V_{xg} & V_{xb} \\ V_{yr} & V_{yg} & V_{yb} \\ V_{zr} & V_{zg} & V_{zb} \end{bmatrix}^{-1} \left(\begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix} - \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} \right) . \quad (6)$$

In our previous works [5]-[7], the accuracy of the calibration is evaluated by comparing the color between the printed color and the projected color by using Macbeth ColorChecker as shown in Figure 7. The average color difference was ΔE^*_{94}=0.73 and the maximum color difference was ΔE^*_{94}=1.72 in our projector system.

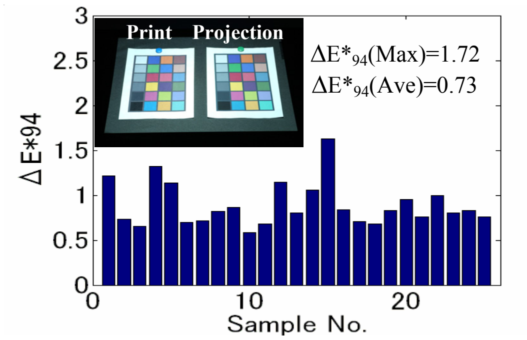

Fig. 7 Accuracy of projector calibration by using Machbeth ColorChecker

3. Calculation of the projection image onto the current print

Figure 8 shows the schematic illustration of projection-based color simulator by projecting the image onto the current print. The projector illuminates the target print by white light from projector. The projector also illuminates the current print by image from projector. The reflected radiance to the observer L_e is calculated by the multiplication between the radiance of projector and the reflectance of print as follows,

$$L_e(x, y, \lambda) = L_i(x, y, \lambda)R(x, y, \lambda) \ , \quad (7)$$

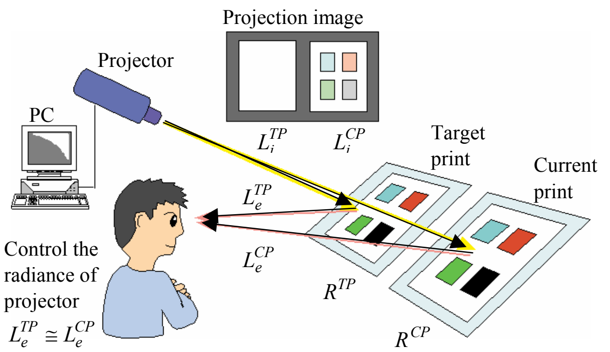

Fig.8 Process of color simulation by controlling the radiance of projector

where, L_i is the radiance of projector, R is the reflectance of print, λ is wavelength from 400nm to 700nm in 10nm interval and x, y denote the image coordinate system defined on the screen. In Figure 8, the radiance L_e^{TP} denotes the reflected radiance from the target print (TP) and L_e^{CP} denotes reflected radiance from the current print (CP). In this paper, the radiance L_e^{TP} of target print is used as the target radiance calculated by print simulator. Therefore, in the color simulator, the radiance L_i^{CP} from the projector onto the current print should be controlled to match the colors between L_e^{CP} and L_e^{TP}.

For the calculation of radiance L_i^{CP} from the projector, it is necessary to consider two methods, one is the spectral-based method where the reflectance of the current print is measured by spectrophotometer, and the other is tristimulus-based method where the reflectance is measured by RGB camera or RGB scanner.

3.1 Spectral-based method

In spectral-based method, the spectral radiant distribution of projector is measured by spectroradiometer and the spectral reflectance of print is measured by spectrophotometer. For the color simulation as shown in Figure 8, the reflected radiance $L_e^{CP}(\lambda)$ from current print (CP) is written as follows,

$$\begin{aligned} L_e^{CP}(\lambda) = {} & C_r^{CP}(d_r^{CP})V_r(\lambda)R^{CP}(\lambda) + C_g^{CP}(d_g^{CP})V_g(\lambda)R^{CP}(\lambda) \\ & + C_b^{CP}(d_b^{CP})V_b(\lambda)R^{CP}(\lambda) + L_o(\lambda)R^{CP}(\lambda) \ , \end{aligned} \quad (8)$$

where $R^{CP}(\lambda)$ is the reflectance of current print. The reflected radiance $L_e^{TP}(\lambda)$ from the target print can be also written as follows,

$$\begin{aligned} L_e^{TP}(\lambda) = {} & C_r^{TP}(d_r^{TP})V_r(\lambda)R^{TP}(\lambda) + C_g^{TP}(d_g^{TP})V_g(\lambda)R^{TP}(\lambda) \\ & + C_b^{TP}(d_b^{TP})V_b(\lambda)R^{TP}(\lambda) + L_o(\lambda)R^{TP}(\lambda) \ , \end{aligned} \quad (9)$$

where $R^{TP}(\lambda)$ is the reflectance of target print. To match the color between the color of target print and current print, the reflected radiance of current print $L_e^{CP}(\lambda)$ should be matched to the reflected radiance of target print $L_e^{TP}(\lambda)$.

The projection image onto the current print is determined by the values of $C_r^{CP}(d_r^{CP}), C_g^{CP}(d_g^{CP}), C_b^{CP}(d_b^{CP})$ to match the colors between $L_e^{CP}(\lambda)$ and $L_e^{TP}(\lambda)$. The colors of $L_e^{CP}(\lambda)$ can be calculated by using XYZ tristimulus values as follows,

$$X_e^{CP} = C_r^{CP}(d_r^{CP}) \int_{400}^{700} V_r(\lambda) R^{CP}(\lambda) \bar{x}(\lambda) d\lambda$$

$$+C_g^{CP}\left(d_g^{CP}\right)\int_{400}^{700} V_g(\lambda)R^{CP}(\lambda)\overline{x}(\lambda)d\lambda$$
$$+C_e^{CP}\left(d_b^{CP}\right)\int_{400}^{700} V_b(\lambda)R^{CP}(\lambda)\overline{x}(\lambda)d\lambda \ . \quad (10)$$

The stimulus values Y_e^{CP} and Z_e^{CP} can be also calculated as is done by Equation 10 for X_e^{CP}. On the other hand, XYZ tristimulus values for the reflected radiance of target print are calculated as follows,

$$X_e^{TP} = C_r^{TP}\left(d_r^{TP}\right)\int_{400}^{700} V_r(\lambda)R^{TP}(\lambda)\overline{x}(\lambda)d\lambda$$
$$+C_g^{TP}\left(d_g^{TP}\right)\int_{400}^{700} V_g(\lambda)R^{TP}(\lambda)\overline{x}(\lambda)d\lambda$$
$$+C_e^{TP}\left(d_b^{TP}\right)\int_{400}^{700} V_b(\lambda)R^{TP}(\lambda)\overline{x}(\lambda)d\lambda \ . \quad (11)$$

The stimulus value Y_e^{TP} and Z_e^{TP} can be also calculated as is done by Equation 11 for X_e^{TP}.

For the color matching between target color proof and current print with projection image, it is necessary to determine projection image for current print to match the reflected radiance $X_e^{TP}, Y_e^{TP}, Z_e^{TP}$ and $X_e^{CP}, Y_e^{CP}, Z_e^{CP}$, respectively. Therefore, the relationship between these radiances is written in Equation 12,

$$\begin{bmatrix} X_e^{TP} \\ Y_e^{TP} \\ Z_e^{TP} \end{bmatrix} = \begin{bmatrix} X_e^{CP} \\ Y_e^{CP} \\ Z_e^{CP} \end{bmatrix} = \begin{bmatrix} A_{xr} & A_{xg} & A_{xb} \\ A_{yr} & A_{yg} & A_{yb} \\ A_{zr} & A_{zg} & A_{zb} \end{bmatrix} \begin{bmatrix} C_r^{CP}\left(d_r^{CP}\right) \\ C_g^{CP}\left(d_g^{CP}\right) \\ C_b^{CP}\left(d_b^{CP}\right) \end{bmatrix} + \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix}, \quad (12)$$

where

$$A_{mn} = \int_{400}^{700} V_n(\lambda)R^{CP}(\lambda)\overline{m}(\lambda)d\lambda \quad (m = x, y, z, \quad n = r, g, b) \ .$$
(13)

As is described in Section 2, the coefficients $C_r^{CP}\left(d_r^{CP}\right), C_g^{CP}\left(d_g^{CP}\right), C_b^{CP}\left(d_b^{CP}\right)$ are calculated from $X_e^{TP}, Y_e^{TP}, Z_e^{TP}$ by using the inverse matrix of PCA-spline model.

3.2 Tristimulus-based method

In spectral-based method, the reflectance of current print needs to be measured by spectral camera or spectral scanner. However, the spectral camera or spectral scanner is not usually available and expensive. An alternative method by using RGB camera or RGB scanner is expected to be used for practical system to reduce the cost of the system. Therefore, we propose the tristimulus method where the reflectance of current print is alternatively measured by RGB camera or RGB scanner.

In this paper, it is assumed that the RGB camera or RGB scanner outputs linear responses, and conversion from RGB response to XYZ tristimulus values is performed by 3×3 linear matrix transformation. We proposed to approximate the reflected radiance $X_e^{CP}, Y_e^{CP}, Z_e^{CP}$ from current print illuminated by projector $X_i^{CP}, Y_i^{CP}, Z_i^{CP}$ as follows,

$$\begin{bmatrix} X_e^{CP} \\ Y_e^{CP} \\ Z_e^{CP} \end{bmatrix} = \begin{bmatrix} X_R^{CP} & 0 & 0 \\ 0 & Y_R^{CP} & 0 \\ 0 & 0 & Z_R^{CP} \end{bmatrix} \begin{bmatrix} X_i^{CP} \\ Y_i^{CP} \\ Z_i^{CP} \end{bmatrix}, \quad (14)$$

where $X_R^{CP}, Y_R^{CP}, Z_R^{CP}$ indicate the reflection ratio of current print as Equation 15,

$$X_R^{CP} = X_e^{CP} \big/ X_e^{W}, \quad Y_R^{CP} = Y_e^{CP} \big/ Y_e^{W}, \quad Z_R^{CP} = Z_e^{CP} \big/ Z_e^{W} \ . \quad (15)$$

The value of X_e^W, Y_e^W, Z_e^W is the reflected radiance from white paper measured by digital camera. It is noted that $X_e^{CP}, Y_e^{CP}, Z_e^{CP}$ and X_e^W, Y_e^W, Z_e^W must be measured under the same illumination.

On the other hand, as is shown in Equation 4, the radiance of projector onto current print $X_i^{CP}, Y_i^{CP}, Z_i^{CP}$ is also written by using the PCA-Spline model as follows,

$$\begin{bmatrix} X_i^{CP} \\ Y_i^{CP} \\ Z_i^{CP} \end{bmatrix} = \begin{bmatrix} V_{xr} & V_{xg} & V_{xb} \\ V_{yr} & V_{yg} & V_{yb} \\ V_{zr} & V_{zg} & V_{zb} \end{bmatrix} \begin{bmatrix} C_r(d_r^{CP}) \\ C_g(d_g^{CP}) \\ C_b(d_b^{CP}) \end{bmatrix} + \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} . \quad (16)$$

By substituting Equation 16 into the Equation 14, we can obtain the following equation,

$$\begin{bmatrix} X_e^{CP} \\ Y_e^{CP} \\ Z_e^{CP} \end{bmatrix} = \begin{bmatrix} X_R^{CP} & 0 & 0 \\ 0 & Y_R^{CP} & 0 \\ 0 & 0 & Z_R^{CP} \end{bmatrix} \left[\begin{bmatrix} V_{xr} & V_{xg} & V_{xb} \\ V_{yr} & V_{yg} & V_{yb} \\ V_{zr} & V_{zg} & V_{zb} \end{bmatrix} \begin{bmatrix} C_r^{CP}(d_r^{CP}) \\ C_g^{CP}(d_g^{CP}) \\ C_b^{CP}(d_b^{CP}) \end{bmatrix} + \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} \right] . \quad (17)$$

For the color matching between the target print and current print with image projection, it is necessary to determine the projection image for current print to match the reflected radiance $X_e^{TP}, Y_e^{TP}, Z_e^{TP}$ and $X_e^{CP}, Y_e^{CP}, Z_e^{CP}$. Therefore, we exchange the $X_e^{TP}, Y_e^{TP}, Z_e^{TP}$ instead of $X_e^{CP}, Y_e^{CP}, Z_e^{CP}$ in Equation 17. As the reflected radiance of target print $X_e^{TP}, Y_e^{TP}, Z_e^{TP}$ has already known, the desired projection image onto the current print can be obtained by using the following equation,

$$\begin{bmatrix} C_r^{CP}(d_r^{CP}) \\ C_g^{CP}(d_g^{CP}) \\ C_b^{CP}(d_b^{CP}) \end{bmatrix} = \begin{bmatrix} V_{xr} & V_{xg} & V_{xb} \\ V_{yr} & V_{yg} & V_{yb} \\ V_{zr} & V_{zg} & V_{zb} \end{bmatrix}^{-1} \left[\begin{bmatrix} X_R^{CP} & 0 & 0 \\ 0 & Y_R^{CP} & 0 \\ 0 & 0 & Z_R^{CP} \end{bmatrix}^{-1} \begin{bmatrix} X_e^{TP} \\ Y_e^{TP} \\ Z_e^{TP} \end{bmatrix} - \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} \right] . \quad (18)$$

4. Evaluation of two color matching methods

For the comparison of spectral-based method and tristimulus-based method, we examine each method by using the computer simulation. To match the color between target and current print, the XYZ tristimulus value of projection image is determined by using Equation 12 for spectral-based method and Equation 17 for tristimulus-based method. Finally, we can estimate the corrected radiance in Equation 7 by projecting final image onto the current print. The estimated radiance and target radiance are compared by using the color differences, which is calculated by CIE color difference ΔE^*_{94} [15]. Therefore, it is clear that the accuracy for two methods is verified with this simulation.

Figure 9 shows the result of the color difference with spectral-based method and tristimulus-based method. The labels on the bar show the combination of target print and current print with dot area percentage in this figure, where the reflectances are measured by portable spectrophotometer (SpectroLino, GretagMacbeth). The samples are printed with 100%, 70%, 40% and 20% dot area halftone of C, M, Y, K, MY, CY, CM and CMY, respectively. The sample of dot area with 0% means a white paper in this figure. The average color difference ΔE^*_{94} is 0.27 by using the spectral-based method, and the average color difference ΔE^*_{94} is 2.09 by tristimulus-based method. In Figure 9, the spectral-based method is accurate in all the color samples because neither the hypothesis nor the approximation is used for the calculation. On the other hand, the tristimulus-based method is accurate for estimation of gray in color, however the accuracy of estimation is decreased in proportion to the saturation of color. The difference between gray and high saturated color is caused by the smoothness of spectral distribution in the range of XYZ color matching functions. Since the integral operation of XYZ calculation loses the spectral variation of the high saturated color, the XYZ tristimulus values calculated by Equation 12 and Equation 17 are different each other depending on the smoothness of spectral distribution. Therefore, tristimulus-based method is not accurate in the estimation of target and current color, and its error increases depending on the saturation of color compared with the spectral-based method.

5. Experimental result for practical color simulator

Figure 10 shows an experimental system of practical color simulator. High radiance projector EMP-TW200H (EPSON) is used in our experiment and this projector is set on the top of system. The radiance of projector was calibrated by the white balance correction which is set the white point of projection image to the D_{50} in Yxy coordinate. The luminance distribution of the projector is made uniform by applying weight to each pixel [5], and the distortion for projection image is also calibrated by using the keystone correction [16]. In this experiment, we evaluate the color simulation in comparison with the target print and current print. The target print which is printed 70% dot area halftone is set to the lower row, and the current print which is printed 40% dot area halftone is set to the upper row, respectively. The color matching is performed by projecting the calculated image onto the current print to match the color each other.

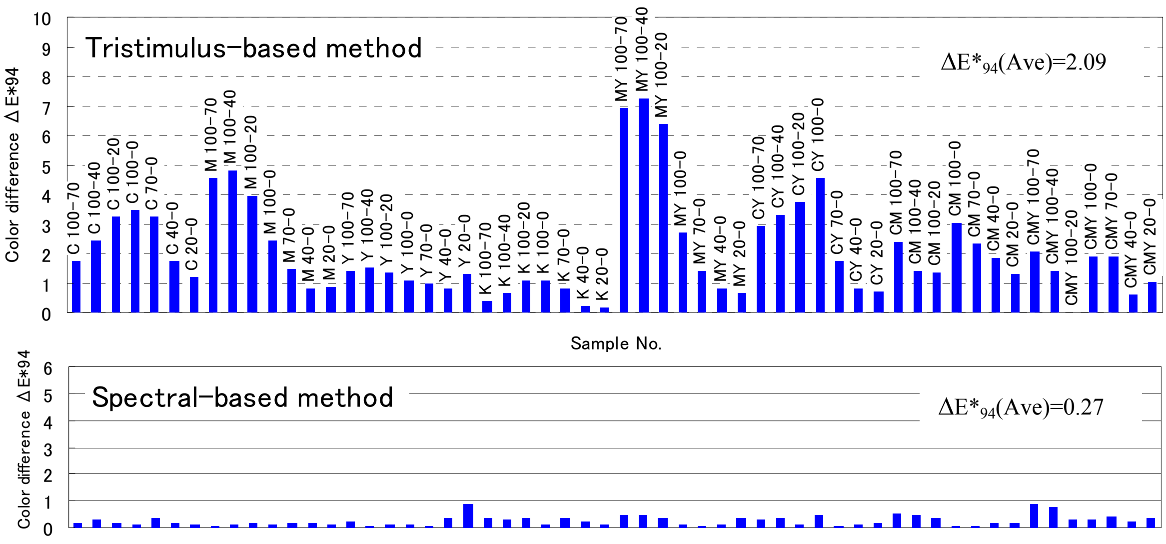

Fig. 9 Results of the color difference between estimated color and target color

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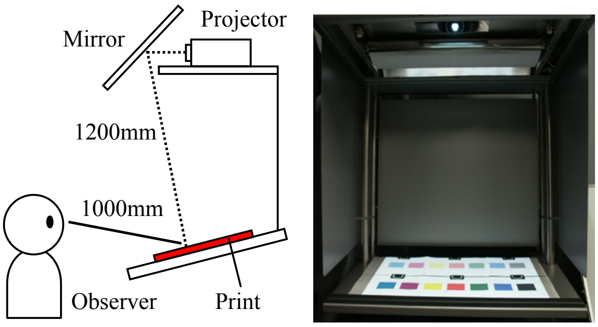

Fig. 10 Observation geometry and overview of experimental system

At the initial condition, both prints are illuminated by white light of the projector. It is clear that reflected color is different each other as shown in Figure 11(a). The radiance of projector and reflectance of current print have already measured by spectroradiometer or colorimeter, and desired projection image onto the current print is calculated in personal computer to control the projection image. Figure 11(b) shows the result of color matching by using the spectral-based method, and Figure 11(c) shows the result of color matching by using the tristimulus-based method. The observer cannot distinguish the color difference between the target print and current print by projecting the calculated image onto the current print in the spectral-based method. On the other hand, a slight difference is recognized at the Cyan color in the tristimulus-based method.

The reflected radiances of each color are measured by CS-1000 spectroradiometer (KONICA MINOLTA) from the position of observer. Figure 12 shows the result of the color difference ΔE^*_{94} between the target print and current print by projecting image onto the current print. The average color difference ΔE^*_{94} by using the spectral-based method is 1.27, and tristimulus-based method is 1.88. Though a remarkable difference of both methods can't be indicated in the average, the accuracy of the spectral-based method is better than the tristimulus-based method in C, MY and CM color, especially.

6. Discussion and conclusion

In this paper, we developed the new projector-based display, which can change the color of current print by projecting the image and can match the color of current print with digital color proof. For the calculation of projection image onto the current print, we evaluated the color difference to target print by using the spectral-based method or the tristimulus-based method based on the

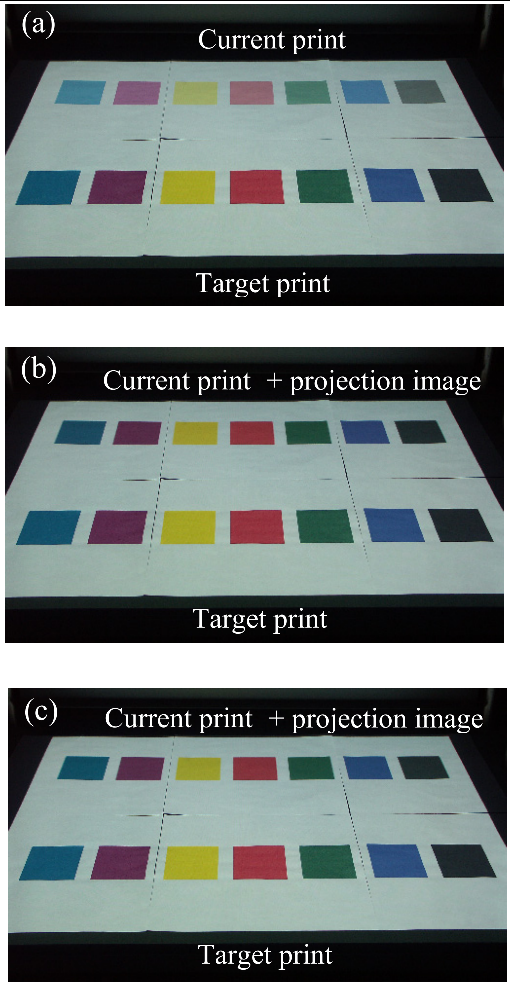

Fig. 11 Result of color simulator to match the color between the target print and current print
(a) Initial condition of experiment
(b) using the spectral-based method
(c) using the tristimulus-based method

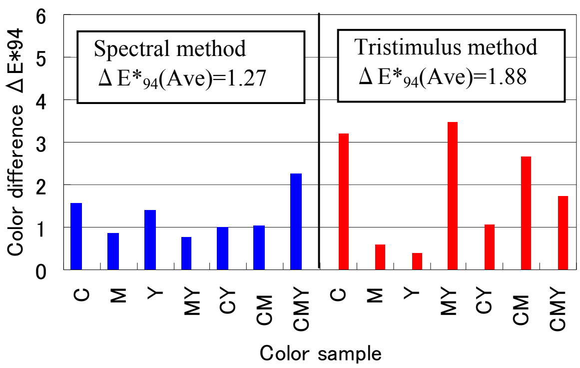

Fig. 12 Result of color difference between the color of target and current print by projecting the calculated image

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† Graduate School of Science and Technology, Chiba University
1-33, Yayoi-cho, Inage-ku, Chiba, 263-8522
††Research Center Frontier Medical Engineering, Chiba University
1-33, Yayoi-cho, Inage-ku, Chiba, 263-8522

computer simulation. As the result, the average color difference ΔE^*_{94} was 0.27 by using the spectral-based method, and the average color difference ΔE^*_{94} was 2.09 by using the tristimulus-based method. The spectral-based method was accurate in all the color samples. On the other hand, the tristimulus-based method was accurate for estimation of gray in color, however the accuracy of estimation was decreased in proportion to the saturation of color. In Figure 9, it is seen that the errors were increased depending on the saturation or ink types compared with the spectral-based method. We thought that dependency was caused by differences of the smoothness in spectral distribution within the range of XYZ color matching functions

By using the two color matching method, we performed the practical experiment of color simulator to match the color between the target print and current print. The average color difference ΔE^*_{94} was 1.27 by using the spectral-based method, and the average color difference ΔE^*_{94} was 1.88 by using the tristimulus-based method. From the result by using the spectral-based method, it was clear that the accuracy of color matching mostly depends on the accuracy of projector calibration as shown in Figure 7 and the accuracy of color matching calculation as shown in Figure 9. If we assume the tolerance of color difference ΔE^*_{94} to be less than 3, it is applicable only in printed color below 40% dot area halftone by using the tristimulus-based. On the other hand, it is applicable for most of printed color by using the spectral-based method.

As the discussion of proposed system, it is important to overcome the difference of the resolution between projection image and current print. In this paper, we examined the color simulation for simple image such as square patch. For the practical use, the influence of the registration error cannot be ignored. It is difficult to decrease the registration error since this problem depends on the resolution of projector. We will develop a correction method for the registration error based on the visual mechanism for spatial frequency in our future work.

In addition, there are problems to clarify such as metamerizm and the color rendering properties of projector. However, these problems will be possible to solve by using this system as the standard. Since our proposed system can match the visual mode and color accurately between the digital color proof and current print, it is suitable to be used as the standard display system to correct and control the printed color for the printing industry.

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Shoji Yamamoto received his B.E. and M.E. degrees from the Department of Opt-Electro-Mechanics Engineering from Shizuoka University in 1989 and 1991 respectively. Now, he is a PhD candidate in Chiba University. He is interested in Multi-spectral imaging, Visual mechanism, and Mixed-reality. He is a member of the Institute of Image Electronics Engineers of Japan.

Kumiko Ueda received B.E. degree in department of information and image science in 2004 and received M.E. degree in graduate school of science and technology in 2006 from Chiba University. She is interested in color reproduction and multi spectral imaging.

Norimichi Tsumura received the B.E., M.E. and Dr. Eng degrees in applied physics from Osaka University in 1990, 1992 and 1995, respectively. He moved to the Department of Information and Computer Sciences, Chiba University in April 1995, as an assistant professor. He is currently associate professor in Department of Information and Image Sciences, Chiba University since February 2002. He got the Optics Prize for Young Scientists (The Optical Society of Japan) in 1995, Applied Optics Prize for the excellent research and presentation (The Japan Society of Applied Optics) in 2000, Charles E. Ives Award (Journal Award: IS&T) in 2002, 2005. He is interested in the color image processing, computer vision, computer graphics and biomedical optics.

Toshiya Nakaguchi was born in Hyogo Prefecture, Japan, on April, 1975. He received the B.E., M.E., and Ph.D. degrees from Sophia University, Tokyo, Japan in 1998, 2000, and 2003, respectively. He is currently a Research Associate in the Department of Information and Image Sciences, Chiba University, Japan. His research interests include medical engineering, color image processing, computer vision and computer graphics. Dr. Nakaguchi is a member of the IEEE, IS&T, the Institute of Electronics, Information and Communication Engineers (IEICE), Japan and Society of Photographic Science and Technology of Japan.

Yoichi. Miyake is the Director of the Research Center for Frontier Medical Engineering and Professor of Image Science at Chiba University. He received Ph.D. from Tokyo Institute of Technology in 1978. He is a Fellow of IS&T. In 2003, he became honoree member of IS&T. In January 2000, IS&T and SPIE, named him as the Electronic Imaging Honoree of the Year. He was served as president of SPSTJ from 1999 to 2001 and as vice president of IS&T from 2000 to 2004. He was also served as guest professor of University of Rochester, USA in 1997, and Chulalongkorn University, Thailanf from 1998 to 2004. He published 20 books on the image analysis and color science.