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Color Correction of Images Projected on a Colored Screen for Mobile Beam Projector

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Abstract. *With the current trend of digital convergence in mobile phones, mobile manufacturers are researching how to develop a mobile beam projector to cope with the limitations of a small screen size and to offer a better feeling of movement while watching movies or satellite broadcasting. However, mobile beam projectors may project an image on arbitrary surfaces, such as colored walls and papers, not only on a white screen as is mainly used in an office environment. Thus, a color correction method for the projected image is proposed to achieve good image quality irrespective of the surface color. Initially, luminance values of the original image in the YCbCr color space are changed to prevent unnatural luminance reproduction of the projected image, depending on the contrast and luminance of the surface image captured with a mobile camera. Next, the chromaticity values for the captured surface and white screen images are calculated using a ratio of the sum of three RGB values compared to one another. Then, their chromaticity ratios are multiplied by the converted image through an inverse YCbCr matrix to reduce the influence of modulating the color tone of the projected image due to spatially different reflectances on the surface. By projecting the compensation image on a texture pattern or single color surface, the image quality of the projected image can be improved, compared to that of the projected image on a white screen.* © *2008 Society for Imaging Science and Technology.*
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INTRODUCTION

To improve the color fidelity and image quality of mobile displays, mobile manufacturers have focused mainly on developing the contrast ratio, screen size, backlight source, and viewing angle. In particular, with the appearance of digital convergence, which has various imaging devices in miniature, new areas in color technology have been exploited by considering the influence of illumination level under outdoor conditions, and increasing the ability of color consistency between mobile camera and mobile display.[1,2] Recently, as a part of digital convergence, mobile beam projectors are being developed to relax the restriction of small screen size and to provide an improvement in realism for users when watching movies or satellite broadcasting. However, poor color fidelity, due to a small lens, lower backlight luminance, and line artifacts, has become an obstacle to making progress in this research. In addition, the projected image significantly suffers from flare, which is defined as some of the ambient light reflected from the white screen, thereby washing out its color.

To overcome these problems, an approach consisting of device characterization and flare calculation, referred to as colorimetric color matching, was suggested to match the colors emitted from a mobile beam projector with those from a reference data projector with a higher price.[3] Accordingly, an LCD based beam projector with poor performance was replaced with a mobile beam projector for experiments in virtual simulation. Conventional characterization, such as gain offset gamma (GOG) and the S curved model, were also used to estimate the tristimulus values reflected from the white screen, and the amounts of the flare represented as the CIE XYZ value were calculated according to the CIE 122 1996.[4]

In spite of these efforts, mobile beam projectors are being confronted with a new problem in that the colors of the projected image are individually modulated by spatial variation of the reflectance of the colored screen. Various algorithms have been proposed with commercial data projectors, and the compensated projection image has been reproduced on colored screens by changing the pixel values of the original image. Nayar et al. presented a color correction method using the radiometric model of a projector camera system, where the radiometric model was represented using a single nonlinear monotonic response function. This means that the mapping function from input digital space to captured digital space can be created by displaying a set of 255 display images on a colored screen in quick succession and recording their corresponding camera images.[5] Assuming that one would like the projector to reproduce the original image on the colored screen, the inverse response function taking the original image as the input value is used to compute the compensation image. Bimber et al. proposed another radiometric based compensation, which found the electro-optical transfer function (EOTF) of each camera and projector, and divided the luminance values of the original image by those of the captured color screen, thus providing the compensation image.[6] Tsukada and Tajima proposed the color reproduction method using color appearance models.[7] When observers see an image projected onto a screen, they perceive the colors of the image while their eyes adapt to the colors on the screen to some degree. Using this concept, color

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matching algorithms, such as von Kries, RLAB, and CIECAM02, are applied on the original image to achieve the color consistency between two images projected on a white screen and a colored screen. The above methods require accurate sensor characterization to predict the CIE XYZ values or luminance values of the projected image on a colored screen. However, if the color sensor is replaced by a mobile camera to cut down on costs and accommodate limited space, large errors between measured data and estimated data occur due to the camera noise, low dynamic range, and poor modulation transfer function of the mobile camera. Thus, another approach based on the YCbCr color space, not on the XYZ color space or luminance color space, was attempted to enable this algorithm to be applied to a mobile phone. In this color space, the luminance values of the original image were initially corrected to prevent spatial modulation of the luminance distribution of the projected image. Next, the chromaticity triplets of the corrected image were adjusted to reduce the influence of modulating the color tones of the projected image by adopting the concept of the color invariant model, which seeks transformation of image data independent of the illumination.[8]

In image acquisition, the camera response depends on three factors: the surface properties of the object, the camera sensitivity function, and the light source. Especially, a change in the light source can make a captured image appear reddish or bluish according to its color temperature. If multiple light sources are illuminating the scene from different directions, inherent surface colors change with spatial position. This kind of physical effect is similar to image formation from a beam projector, where projected images are reproduced with the backlight source and filter characteristics of the beam projector in addition to the screen material. In a mobile environment, spatially varying surface colors can modulate the color tones of the projected image, similar to the effect of multiple light sources in an image acquisition. From this point of view, the approach of using the color invariant model to remove the influence of illumination in image acquisition can provide a pathway for achieving this study's goals.

The remainder of this paper is organized as follows. The first section will provide an outline of conventional methods, and then the possibility of applying them to a mobile phone will be examined by investigating the performance of time-varying beam projector characterization. Next, the proposed method based on the luminance compensation and chromaticity correction will be introduced. In the section of experimental results, the performance of the proposed method will be quantitatively evaluated for single color surfaces and a texture pattern. Finally, the conclusion will be presented in the conclusion section.

OVERVIEW OF CONVENTIONAL METHODS

Considering that the projector outputs only grayscale images, the luminance values of the compensation image projected on a colored screen should be the same as the luminance values of the original image projected on a white screen for radiometric compensation:

$$I_b^c(x,y)R_c(x,y) = I_b^o(x,y)R_w(x,y), \tag{1}$$

where $I_b^c(x,y)$ and $I_b^o(x,y)$ represent the luminance values corresponding to the compensation image and the original image at the same spatial position for the beam projector, and $R_c(x,y)$ and $R_w(x,y)$are the reflectances of the color screen and the white screen, respectively. Assuming the white screen reflects an equal amount of incident light independent of spatial position, i.e., $R_w(x,y)=1$, the luminance values of the compensation image can be described as

$$\begin{aligned} I_b^c(x,y) &= \frac{I_b^o(x,y)}{R_c(x,y)}, \\ f_b(d_b^o(x,y)) &= I_b^o(x,y). \end{aligned} \tag{2}$$

If the EOTF of the beam projector is modeled with device characterization and is expressed as a function of f_b, $I_b^o(x,y)$ can be calculated by taking the digital value of the original image, $d_b^o(x,y)$, as an input value of the function. In Eq. (2), $R_c(x,y)$ can be described as the linearized captured digital value if the camera response function is given as a function of f_c and the luminance value corresponding to the white signal is independent of spatial position, $I_b^w(x,y)=1$:

$$\begin{aligned} f_c(I_b^w(x,y)R_c(x,y)) &= d_c^w(x,y), \\ R_c(x,y) &= f_c^{-1}(d_c^w(x,y)), \end{aligned} \tag{3}$$

where $d_c^w(x,y)$ indicates the digital value of the captured image by projecting the white signal onto the colored screen. In conclusion, the compensation image $d_b^c(x,y)$ can be obtained by substituting Eq. (3) into Eq. (2):

$$d_b^c(x,y) = f_b^{-1}(I_b^c(x,y)) = f_b^{-1}\left[\frac{f_b(d_b^o(x,y))}{f_c^{-1}(d_c^w(x,y))}\right]. \tag{4}$$

On the other hand, the appearance based compensation method converts the luminance values of each camera and beam projector into the CIE XYZ values to reflect the function of chromatic adaptation in the human visual system. The compensation image, having the CIE XYZ values the same as those of the original image projected on a white screen, was calculated with a color appearance model, and thus color matching between the two projected images could be completed.

TIME-VARYING MOBILE BEAM PROJECTOR CHARACTERIZATION

Conventional methods require the accurate estimation of the CIE XYZ values or linearized RGB values corresponding to the input signals, and thus an expensive color sensor has to be built into the data projector. In the case of mobile beam projectors, mobile cameras can be effectively used to cut down costs and adapt to a limited space. In this section, the

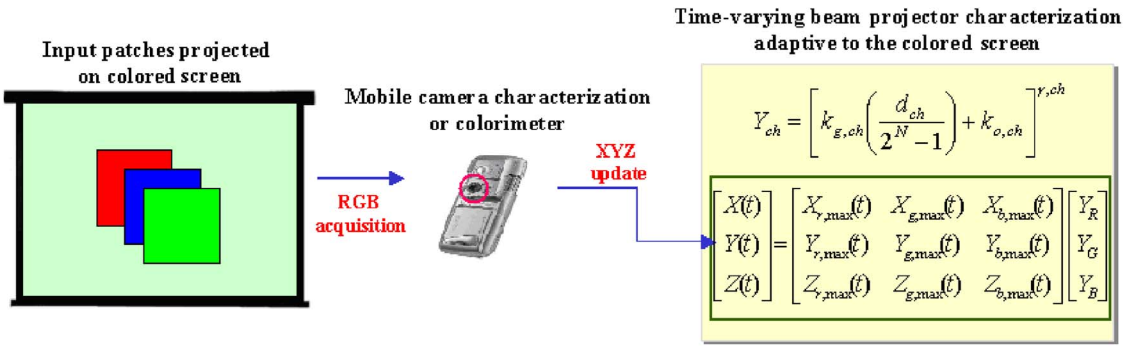


Figure 1. Time varying mobile beam projector characterization.

Table I. Measured luminance values on four color screens.

Input Control Signal			Luminance Values on Four Color Screens			
R	G	B	Blue	Green	Red	White
0	0	0	0.003	0.003	0.003	0.003
0	0	51	0.005	0.005	0.005	0.005
0	0	102	0.011	0.010	0.010	0.010
0	0	153	0.024	0.021	0.020	0.021
0	0	204	0.048	0.040	0.039	0.041
0	0	255	0.064	0.055	0.053	0.055
0	51	0	0.026	0.026	0.025	0.026
0	102	0	0.104	0.107	0.101	0.104
0	153	0	0.256	0.263	0.245	0.256
0	204	0	0.507	0.520	0.486	0.506
0	255	0	0.776	0.798	0.754	0.779
51	0	0	0.009	0.009	0.011	0.010
102	0	0	0.029	0.028	0.034	0.031
153	0	0	0.065	0.063	0.078	0.069
204	0	0	0.121	0.117	0.146	0.128
255	0	0	0.186	0.180	0.225	0.198
51	51	51	0.034	0.034	0.035	0.034
102	102	102	0.138	0.138	0.138	0.138
153	153	153	0.331	0.331	0.331	0.331
204	204	204	0.661	0.660	0.659	0.659
255	255	255	1.000	1.000	1.000	1.000

possibility of their use was investigated based on the performance of the mobile camera characterization, and the beam projector characterization, while adapting to time variation of the screen color, is described with a more detailed study given the limited content of the previous paper.[7]

Figure 1 shows the beam projector characterization with the mobile camera or colorimeter to update the CIE XYZ values of primary colors in a linear matrix, according to the time-varying screen color. Time-varying beam projector characterization is composed of two steps, similar to that of the beam projector fixed with a white screen. The first step determines the RGB luminance emitted by the backlight or self-luminous body corresponding to the input control signals. Even though the surface color varies with time, the increasing rates of normalized luminance values according to the input control signals are almost the same, as shown in Table I, where input RGB digital values are sampled based on the interval of 51 for each channel and four printed papers are used as colored screens, as shown in Figure 2. A small difference between the measured luminance values exists, yet visual examination cannot discriminate among them, as will be verified in the evaluation of the beam projector characterization. Therefore, this processing can be completed by conventional methods, which require estimat-

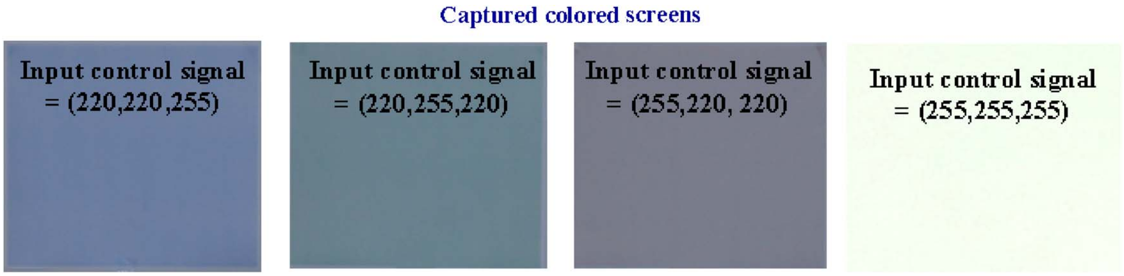


Figure 2. Various colored screens captured by mobile camera.

ing the coefficients of mathematical models, such as GOG or S curve with a limited number of data measurements.[9,10] For example, with the GOG model, the mathematical function is described as

$$Y_{\mathrm{ch}} = \left[k_{g,\mathrm{ch}} \left(\frac{d_{\mathrm{ch}}}{2^N - 1} \right) + k_{o,\mathrm{ch}} \right]^{\gamma,\mathrm{ch}}, \tag{5}$$

where *ch* represents the RGB channel, d_{ch} is the input digital value, and N is the bit number; $(k_{g,\mathrm{ch}}, k_{o},_{\mathrm{ch}}, \gamma)$ are the gain, offset, and gamma parameters, respectively. Y_{ch} is the normalized luminance value corresponding to the normalized input digital value for each channel.

The second step transforms the estimated luminance values to the CIE XYZ values through the linear matrix operation:

$$\begin{bmatrix} X(t) \\ Y(t) \\ Z(t) \end{bmatrix} = \begin{bmatrix} X_{r,\max}(t) & X_{g,\max}(t) & X_{b,\max}(t) \\ Y_{r,\max}(t) & Y_{g,\max}(t) & Y_{b,\max}(t) \\ Z_{r,\max}(t) & Z_{g,\max}(t) & Z_{b,\max}(t) \end{bmatrix} \begin{bmatrix} Y_R \\ Y_G \\ Y_B \end{bmatrix}. \tag{6}$$

Y_R, Y_G, and Y_B are the luminance values of each channel, and the matrix coefficients in each column are the CIE XYZ values at the maximum digital values of each channel; they can be directly measured with a colorimeter or estimated through the camera characterization. However, these CIE XYZ values are continuously changing with time-varying screen color, and thus the updating processing should occur in real time. If a colorimeter is built into a mobile phone, its use will provide a solution to obtaining adaptive matrix coefficients. To demonstrate this strategy, all three patches made by a maximum digital value of each channel and a black patch were projected onto four papers of different colors: red, green, blue, and white. Then, their CIE XYZ values were measured with a colorimeter and were substituted into Eq. (6), thereby updating the coefficients in the linear matrix. Table II shows the results of the beam projector characterization using the GOG model for the color screens. In this table, the characterization errors are comparable indicative of high performance, and from this result it is recognized that the shape of the tone response curve is independent of surface color, and that the use of the colorimeter can achieve an adaptively good beam projector characterization. However, it is not trivial for the colorimeter to be put to practical use due to the increase in the production cost and space.

Table II. Evaluation of the beam projector characterization for the four color screens.

	Average ΔE^*_{ab}	Maximum ΔE^*_{ab}
Red paper	2.7199	7.8227
Green paper	2.7204	8.1957
Blue paper	2.7947	7.5385
White paper	2.2761	7.8749

The use of a mobile camera can be an effective approach to solving this problem if camera characterization can achieve high accuracy. In mobile camera characterization a linear equation is generally used to define the relation between the linearized RGB digital value and the CIE XYZ value:[11]

$$\begin{aligned} X &= 1 + \alpha_{L,R} R^{\gamma_r} + \alpha_{L,G} G^{\gamma_b} + \alpha_{L,G} B^{\gamma_b}, \\ Y &= 1 + \alpha_{a,R} R^{\gamma_r} + \alpha_{a,G} G^{\gamma_b} + \alpha_{a,G} B^{\gamma_b}, \\ Z &= 1 + \alpha_{b,R} R^{\gamma_r} + \alpha_{b,G} G^{\gamma_b} + \alpha_{b,G} B^{\gamma_b}, \end{aligned} \tag{7}$$

where γ and α represent the gamma values and the coefficients of each channel, respectively. Even though the CCD sensor is inherently a linear electro-optic conversion device, nonlinearity may stem mainly from CRT gamma correction.[12] First, to estimate these gamma values, the reflectance factors, r_i, are measured for N_g grayscale patches in a Gretag ColorChart, and then a least mean square method or other optimization program is applied to these sets of N_g equations:

$$\begin{aligned} \log_{10}(r_i) &= \gamma_R \log_{10} R_i, \\ \log_{10}(r_i) &= \gamma_G \log_{10} G_i, \\ \log_{10}(r_i) &= \gamma_B \log_{10} B_i, \quad i = 1, \ldots, N_g. \end{aligned} \tag{8}$$

In Figure 3, three marks indicate the measured reflectance factors and dotted lines indicate the estimated gamma curves $\gamma_R = 2.28$, $\gamma_G = 2.29$, and $\gamma_B = 2.58$ for each channel, respectively. Next, the coefficients in the linear equation are estimated by substituting the captured RGB values of the Gretag

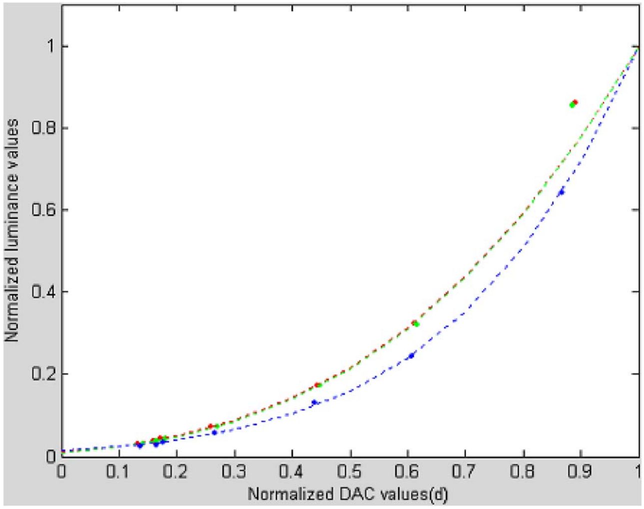


Figure 3. Linearization of a mobile camera.

Table III. Results of the mobile camera characterization.

	Estimated CIE XYZ Values	Measured CIE XYZ Values
Red patch=(255,0,0)	(260,135,2)	(260,144,33)
Green patch=(0,255,0)	(285,580,51)	(305,580,54)
Blue patch=(0,0,255)	(95,29,519)	(63,6,519)

ColorChart and corresponding CIE XYZ values with Eq. (7) and then applying polynomial regression. With the derived gamma values and coefficients, mobile camera characterization is conducted by projecting four patches onto red paper. In Table III, the measured CIE XYZ values are compared with the estimated CIE XYZ values converted into absolute values with a scaling factor, whereby the average color difference between measured and estimated CIE XYZ values is about 13 with a maximum color difference of 44 for test patches. Moreover, the chromaticity values are significantly different from each other, thereby making it difficult to implement accurate device characterization.

THE PROPOSED COLOR CORRECTION OF IMAGES PROJECTED ONTO COLORED SCREENS

In the mobile beam projector, computing time and available memory assigned for a color correction chip are restricted and complicated operations should be avoided as much as possible. Moreover, the compensation images are obtained by changing the only RGB digital values of the original image without any aid of the device or material, and thus it is difficult to achieve good color correction of the projected image on complex surfaces, which include a high frequency component and a wide range of surface reflectance. The color correction method is designed on the assumption that users prefer to project an image on a uniform background or colored screen with slowly varying reflectance for the acquisition of a high quality projection image. Figure 4 shows the block diagram of a proposed algorithm to correct the projected image on a colored screen. Initially, the colored screen and the white screen are captured with a mobile camera and each image size is adjusted to be the same as the original image in order to define the spatial one-to-one mapping; i.e., finding the relation of pixel positions between the captured color screen and the original image. Three factors regarding the contrast, luminance, and chromaticity are then calculated to find the characteristics of the colored screen. Next, the luminance component of the original image in YCbCr color space is changed with contrast and luminance factors to prevent unnatural luminance reproduction of the projected image during the process of luminance compensation. Finally, the corrected luminance component is combined with other color components, and the chromaticity triplet of the converted image through the inverse YCbCr conversion is corrected using a chromaticity factor to reduce any systematic modulation of the color tones of the projected image.

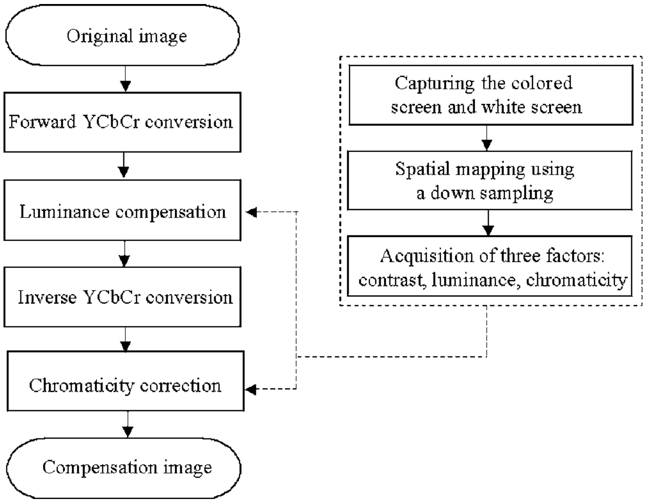


Figure 4. Block diagram of the proposed algorithm.

Spatial Mapping Using Down-Sampling

Spatial mapping is used to find the relation of pixel positions between the captured color screen and the original image. The original image reproduced on a mobile display should be modified depending on the pixel values of the captured colored screen for the acquisition of the compensation image. However, captured images have various image sizes according to the CCD resolution of the mobile camera, different from that of the input original image with a fixed 320 × 240 resolution. Thus, the image size of the captured colored screen should be adjusted to that being displayed in a mobile phone using down-sampling or conventional interpolation:[13]

$$n_1 = \frac{W_c}{W_D}, \quad n_2 = \frac{H_c}{H_D}, \tag{9}$$

$$\mathrm{ColorScreen} = \mathrm{ColorScreen}\left(\frac{x}{n_1}, \frac{y}{n_2}\right), \tag{10}$$

where ColorScreen indicates the colored screen image, and (W_c, H_c) and (W_D, H_D) are the width and height of the ColorScreen and original image, respectively; (n_1, n_2) are the ratios of the width and height between two images, and (x,y) represents the spatial position on the digital image.

Luminance Compensation of the Original Image

The spatially different reflectances on the colored screen, including uniform background, texture pattern or pictures, prevents the projected image from preserving the luminance distribution of the original image. The uniform background darkens the luminance of the projected image in proportion to one constant reflectance, while texture patterns or pictures partially decrease the luminance of the projected image due to the spatially varying reflectances. Accordingly, spatial luminance compensation of the original image should be conducted to preserve the luminance distribution of the original image. First, the original image and the captured colored screen image are converted into grayscale images using conventional color models. One of the color models, the HSI color model is the simplest method to extract the luminance value from the color image; it considers how each RGB channel can have an effect on the overall grayscale. By contrast, the CIELAB color space includes nonlinear computations and is not suitable for hardware implementation, even though the color difference may be homogeneous. Thus, the YCbCr color model, which reflects a visual sensitivity function by imposing a high weight to the G channel in comparison to the R and B channels, is used:

$$\begin{aligned} Y_{\mathrm{ColorScreen}}(x,y) = {} & 0.299R_{\mathrm{ColorScreen}}(x,y) \\ & + 0.587G_{\mathrm{ColorScreen}}(x,y) \\ & + 0.114B_{\mathrm{ColorScreen}}(x,y), \end{aligned} \tag{11}$$

$$\begin{aligned} Y_{\mathrm{original}}(x,y) = {} & 0.299R_{\mathrm{original}}(x,y) + 0.587G_{\mathrm{original}}(x,y) \\ & + 0.114B_{\mathrm{original}}(x,y), \end{aligned} \tag{12}$$

where $Y_{\mathrm{ColorScreen}}$ and Y_{original} are the luminance values of the colored screen image and original image at a pixel position (x,y), respectively. $(R_{\mathrm{ColorScreen}}, G_{\mathrm{ColorScreen}}, B_{\mathrm{ColorScreen}})$ and $(R_{\mathrm{original}}, G_{\mathrm{original}}, B_{\mathrm{original}})$ are the RGB digital values of the colored screen image and original image.

Next, the contrast and luminance factors will be defined to find the luminance range of the colored screen image and the average luminance difference between the white screen image and colored screen image:

$$\begin{aligned} \text{CF (Contrast Factor)} &= \frac{Y_{\mathrm{ColorScreen\_max}} - Y_{\mathrm{ColorScreen\_min}}}{Y_{\mathrm{ColorScreen\_max}} + Y_{\mathrm{ColorScreen\_min}}}, \quad 0 \le \mathrm{CF} \le 1, \\ \text{LF (Luminance Factor)} &= Y_{\mathrm{WhiteScreen\_ave}} - Y_{\mathrm{ColorScreen\_ave}}, \quad 0 \le \mathrm{LF} \le 1, \end{aligned} \tag{13}$$

where $Y_{\mathrm{ColorScreen\_max}}$ and $Y_{\mathrm{ColorScreen\_min}}$ are the maximum and minimum luminance values of the colored screen image, respectively, and $Y_{\mathrm{WhiteScreen\_ave}}$ and $Y_{\mathrm{ColorScreen\_ave}}$ are the average luminance values of the white screen image and colored screen image. In Eq. (13), CF is defined as the contrast of the color screen image, and this factor shows how much the luminance intensity of the projected image is modulated on the colored screen. If the value of CF is close to unity, the colored screen has a wide luminance range, and the luminance distribution of the original image can be distorted leading to unnatural reproduction. If the value of CF is zero, this factor indicates that the colored screen has a single surface color and the luminance distribution of the original image can be preserved. However, the average luminance of the projected image is decreased when the reflectance of the colored screen is lower, and thus another luminance factor, defined as the difference between the average luminance values of the white screen and the colored screen, is needed. These two factors are calculated according to their definitions, and the luminance values of the original image are corrected as follows:

$$\begin{gathered} \text{if } Y_{\mathrm{original\_max}} < Y_{\mathrm{ColorScreen\_min}}, \\ k = -\mathrm{LF} + 1, \\ Y_{\mathrm{corrected\ image}}(x,y) = Y_{\mathrm{original}}(x,y) + k\,\mathrm{LF}, \\ \text{otherwise}, \\ Y_{\mathrm{compressed}}(x,y) = Y_{\mathrm{ColorScreen\_min}} \frac{Y_{\mathrm{original}}(x,y)}{Y_{\mathrm{original\_max}}}, \\ k = -\mathrm{LF} + 1, \\ Y_{\mathrm{corrected\ image}}(x,y) = Y_{\mathrm{compressed}}(x,y)\mathrm{CF} + Y_{\mathrm{original}}(x,y)(1 \\ - \mathrm{CF}) + k\,\mathrm{LF}. \end{gathered} \tag{14}$$

If the maximum luminance value of the original image, $Y_{\mathrm{original\_max}}$, is smaller than the minimum luminance value of the colored screen, the luminance distribution of the projected image can be preserved, similar to that of the original image. However, if the average luminance of the projected image is reduced due to a lower reflectance of the colored screen, the luminance factor is added to the luminance values of the original image for luminance compensation. In this case, if the value of LF is very large, the addition of the value of LF to the luminance values of the original image causes a lot of clipping artifacts; i.e., luminance values in excess of the maximum digital value. To decrease these clipping artifacts, the *k* factor, which is in inverse relation to the value of LF, is multiplied with the luminance factor.

Otherwise, the linearly compressed luminance image $Y_{\mathrm{compressed}}$, according to the ratio of the maximum luminance value of the original image to the minimum luminance of the colored screen, is calculated to produce the projected image with the luminance distribution of the original image. Then, linear interpolation with a weighting factor, expressed as CF, is applied to the compressed image and original luminance image. If the colored screen has a single surface color or uniform background, in other words, the value of CF is zero, a heavy weighting is imposed on the original luminance image because there is no luminance modulation of the projected image, and the value of k LF is added to compensate the decreased luminance of the projected image. If the value of CF is close to 1, the compressed image has a larger weighting to guarantee the luminance distribution similar to that of the original image, and the value of k LF is also added. Following the luminance compensation of the original image, the inverse YCbCr transformation is applied to enable the subsequent processing of the chromaticity correction, where Cb and Cr are the untouched two color signals of the original image:

$$\begin{pmatrix} R(x,y) \\ G(x,y) \\ B(x,y) \end{pmatrix} = \begin{pmatrix} 1 & 0 & 1.402 \\ 1 & -0.34414 & -0.71414 \\ 1 & 1.772 & 0 \end{pmatrix} \times \begin{pmatrix} Y_{\text{corrected image}}(x,y) \\ C_b(x,y) \\ C_r(x,y) \end{pmatrix}. \qquad (15)$$

Chromaticity Correction Using a Color Invariant Model

Assuming that the condition of backlight source and the filter characteristics in the beam projector are constant, the main cause of modulating the colors of the projected image is the spatially varying surface color, different from, e.g., office environments with white screen. One can find that similar physical phenomena occur in image acquisition when the color temperature of the light source illuminating the scene is changed. Camera response depends on the spectral sensitivity $[S(\lambda)]$ of the sensor, the spectral reflectance $[r(\lambda)]$ of objects in the scene, and spectral radiance $[l(\lambda)]$ of the illumination:

$$C_{\text{ch}} = \int_{\lambda_{\min}}^{\lambda_{\max}} l^i(\lambda) r(\lambda) s_{\text{ch}}(\lambda) d\lambda, \quad ch = R,G,B \text{ and } i = \text{D65,A}. \qquad (16)$$

If the daylight source is replaced with an incandescent source under equal conditions, the dominant long wavelengths of the incandescent source make the captured image reddish or yellowish. Moreover, if multiple light sources are illuminating the scene from different directions, inherent surface colors change with spatial position. Thus, the color invariant principle that seeks transformation of image data independent of illumination has been suggested.[6] One such simple method is the so called chromaticity invariant model, which uses scaling factors that give the same chromaticity (r,g,b) triplet independent of the light source. The chromaticity triplet is a sort of color coordinate described as the ratio of the sum of three quantities to one another, not as an absolute quantity:

$$r_i = \frac{R}{R+G+B}, \quad g_i = \frac{G}{R+G+B}, \quad b_i = \frac{B}{R+G+B}, \quad i = \text{D65, A}, \qquad (17)$$

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \begin{bmatrix} r_{\text{D65}}/r_{\text{A}} & 0 & 0 \\ 0 & g_{\text{D65}}/g_{\text{A}} & 0 \\ 0 & 0 & b_{\text{D65}}/b_{\text{A}} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}, \qquad (18)$$

(R,G,B) is the captured RGB digital value under an incandescent source and (R',G',B') is the chromaticity invariant RGB digital value. In each column, the scaling factor is described by the ratio of average chromaticity values for two images captured under different light sources. The concept of the color invariant model can also be applied to accomplish our goal, especially for the chromaticity correction of projected images. First, the white patch projected on a white screen is precaptured by a mobile camera and the chromaticity triplet of the image is calculated at each pixel position. The above process is likewise applied to the captured colored screen to find its chromaticity triplets. Next, the chromaticity triplets of the original image are corrected by multiplying the chromaticity ratio of two images, so that the chromaticity triplets of the projected image on the color screen can be the same as those of the projected image on the white screen:

$$R'(x,y) = R(x,y)\frac{r_{\text{WhiteScreen}}(x,y)}{r_{\text{ColorScreen}}(x,y)},$$

$$G'(x,y) = G(x,y)\frac{g_{\text{WhiteScreen}}(x,y)}{g_{\text{ColorScreen}}(x,y)}, \qquad (19)$$

$$B'(x,y) = B(x,y)\frac{b_{\text{WhiteScreen}}(x,y)}{b_{\text{ColorScreen}}(x,y)},$$

where $(r_{\text{WhiteScreen}}, g_{\text{WhiteScreen}}, b_{\text{WhiteScreen}})$ and $(r_{\text{ColorScreen}}, g_{\text{ColorScreen}}, b_{\text{ColorScreen}})$ are the chromaticity triplets of the white screen image and colored screen image, respectively. By projecting the corrected $R'G'B'$ images on the colored screens, one can obtain resulting images invariant to the surface colors of the screen.

EXPERIMENT

To carry out an experimental evaluation for the proposed algorithm, the EPSON LCD EMP 7600 beam projector was used as a testing device. Large papers printed with different colors are replaced the colored screens, where single color surfaces and a texture pattern with high reflectance were tested to accomplish the goal of simple color correction, in consideration of available memory and computational ability of a mobile phone. Also, the performances of chromatic-

(a)

(b)

(c)

(d)

(e)

(f)

Figure 5. Resulting images using chromaticity correction algorithm: (a) image projected on blue paper; (b) image projected on white paper; (c) corrected image on blue paper; (d) image projected on green paper; (e) image projected on white paper; and (f) corrected image on green paper.

Table IV. Performance of proposed chromaticity correction for blue paper.

	Projected Image on Blue Paper	Projected Image on White Paper	Corrected Image on Blue Paper
Average digital value of R channel	111.43	112.5	110.3
Average digital value of G channel	117.69	111.2	105.19
Average digital value of B channel	124.39	106.9	100.99
r chromaticity	0.315 21	0.340 29	0.348 521
g chromaticity	0.332 918	0.336 358	0.332 375
b chromaticity	0.351 871	0.323 351	0.319 104
Chromaticity error	0.057 04	0	0.016 462

Table V. Performance of proposed chromaticity correction for green paper.

	Projected Image on Green Paper	Projected Image on White Paper	Corrected Image on Green Paper
Average digital value of R channel	100.6	114.4	109.7
Average digital value of G channel	107.4	110.5	100.5
Average digital value of B channel	100.2	107.6	96.74
r chromaticity	0.326 411	0.344 06	0.357 339
g chromaticity	0.348 475	0.332 331	0.327 426
b chromaticity	0.325 114	0.323 609	0.315 176
Chromaticity error	0.035 297	0	0.026 677

ity correction only and of full processing were individually evaluated to understand their functions.

Correction for a Single Color Surface Only

Figure 5 shows the images resulting using chromaticity correction only as a part of our algorithm for uniform blue and green papers. The projected image on blue paper dominantly included the blue color tone, as shown in Figure 5(a), and its image quality deteriorated compared with that of the image on white paper in Figure 5(b); the achromatic region was especially sensitive on visual observation compared to the chromatic region. Figure 5(c) shows the resulting image using chromaticity correction, where the enhanced projected image was reproduced on colored paper across the board, although there was a little chromaticity error due to the incomplete color invariant model. The same effect was observed for a green paper. For quantitative evaluations, the projected images were captured with a digital camera, and their average digital values and corresponding chromaticity values calculated for each channel, as shown in Tables IV and V. The average RGB values of Figures 5(a) and 5(b) may be close to those of Figures 5(b) and 5(e), because corrected images result from the application of the chromaticity correction algorithm, not considering absolute triplet quantity. Yet, the chromaticity errors of the corrected images were considerably reduced compared to those of the uncorrected images projected onto the colored papers. From this result, it is concluded that the chromaticity correction can reproduce the projected image invariant to the surface color.

The Evaluation of Proposed Algorithm for a Texture Pattern

Figure 6 shows the resulting images using the proposed algorithm including the luminance compensation and chromaticity correction. Figure 6(a) shows the texture pattern and Figure 6(b) is the projected image on white paper. In Figure 6(c), the colors of the projected image on a texture pattern were spatially modulated depending on four kinds of color tone, making it hard to see the movie or video broadcast on the surface color. An improved image as shown in Figure 6(d) was obtained through the use of the chromaticity correction algorithm to reproduce the color tone, similar to that shown on the white screen. Yet, it was found that the brightness of that image was decreased slightly owing to use of chromaticity correction only. In contrast, increased average brightness could be achieved with luminance compensation as described above, as along with the correction of color tone, as shown in Figure 6(e). Figure 7 shows the difference in images between the projected image on white paper and other projected images, and the quantitative performances are shown in Table VI. The proposed algorithm using both luminance compensation and chromaticity correction gives a better performance, improving the color tone and brightness of the projected images.

Table VI. Quantitative evaluation of the proposed algorithm.

	Difference Image between Fig. 6(b) and 6(c)	Difference Image between Fig. 6(b) and 6(d)	Difference Image between Fig. 6(b) and 6(e)
Average digital value of R channel	21.00	17.38	11.41
Average digital value of G channel	16.59	15.04	7.43
Average digital value of B channel	19.44	18.08	10.46

CONCLUSIONS

This paper proposed the color correction method for an image projected on a colored screen consisting of both luminance compensation and chromaticity correction. In the luminance compensation, the RGB original image was transformed into the YCbCr color space to extract the luminance values from color signals, and then their luminance values were corrected to preserve the luminance distribution of the original image on the colored screen. In the chromaticity correction, the chromaticity triplet of the image converted by inverse YCbCr transformation was adjusted based on the

(a)

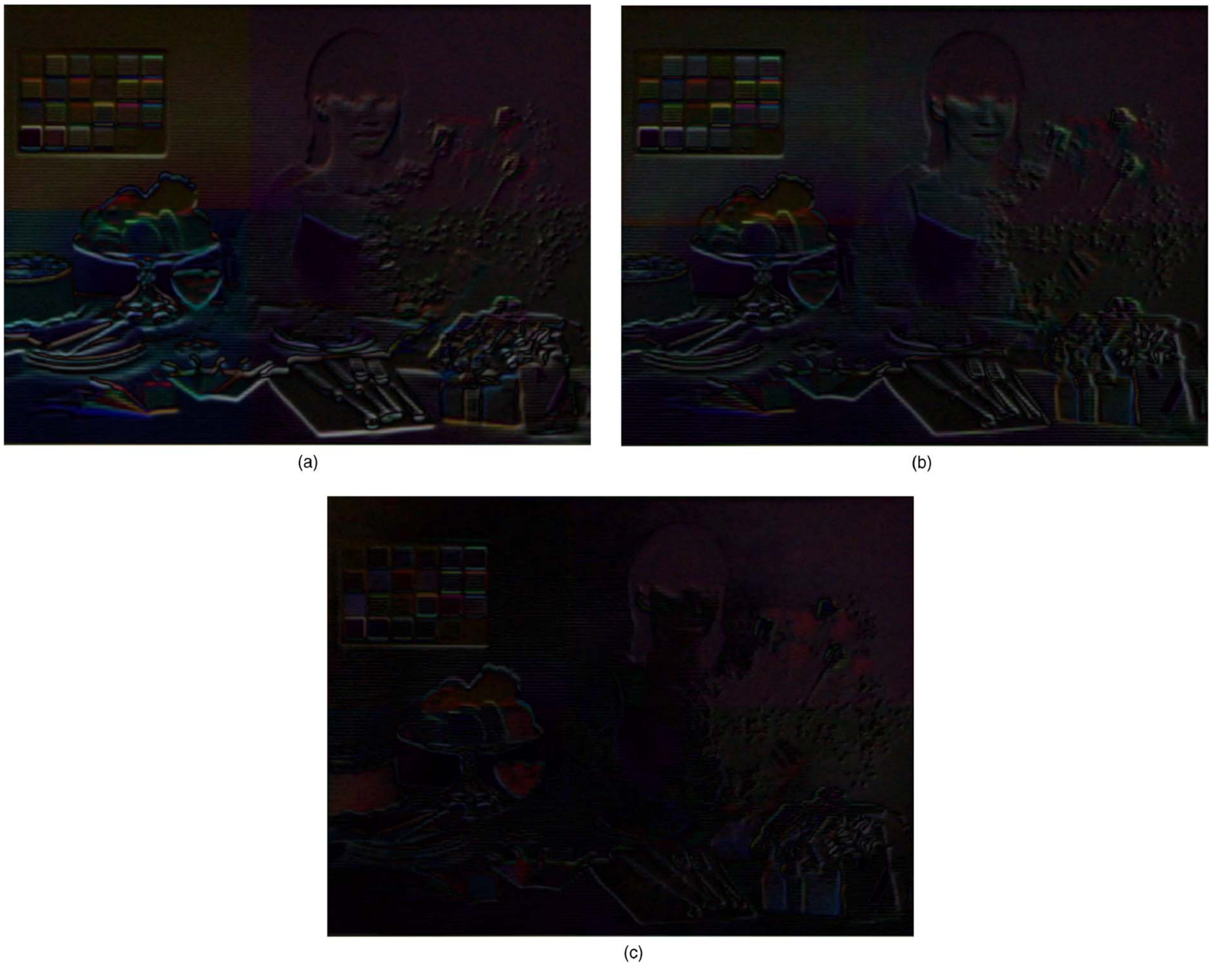
(b)

(c)

(d)

(e)

Figure 6. Resulting images using proposed algorithm: (a) a texture pattern; (b) image projected on white paper; (c) image projected on texture pattern; (d) the resulting image using chromaticity correction; and (e) the resulting image using chromaticity correction and luminance compensation.



(a)

(b)

(c)

Figure 7. Difference images: (a) difference between Fig. 6(b) and 6(c); (b) difference between Fig. 6(b) and 6(d); and (c) difference between Fig. 6(b) and 6(e).

chromaticity invariant representation to reduce any influence of modulation in the appearance of projected images. For both a single color surface and a texture pattern, the experimental results show that the proposed method can reproduce the projected image invariant to the surface color, thereby providing a solution to improve the image quality of beam projectors.

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