Color Conversion Method for Camera-based PDP Color Inspection

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Abstract

A low-cost and high-speed PDP color inspection system can be constructed by using a CCD camera against a colorimeter. Though the inspection can be done using RGB signals obtained by a camera, it has some difficulty to introduce human color sensitivity. Thus, it is quite desirable to convert the RGB values into the XYZ values that can be compared to the values of a colorimeter. Accordingly, the current study proposes a color conversion method that can analytically calculate the RGB-to-XYZ conversion matrix by utilizing the RGB primaries and the reference white. Experiments on Macbeth colorchecker colors showed that the average color difference between the converted XYZ values of the proposed method and the measured XYZ values of a colorimeter is much below the threshold of distinguishing two adjacent color patches.

1. Introduction

In most production lines, the displayed color on a PDP needs to be inspected and evaluated. For automatic inspection, a colorimeter is usually used to measure the output color of a PDP directly. A colorimeter uses three or four silicon sensors that simulate the XYZ tristimulus functions as closely as possible within the constraint of sensitivity loss for improving the spectral match [1]. However, an automatic color inspection system using a colorimeter demands too much costs and requires a long inspection time because the colorimeter must keep contact with a PDP under inspection. Therefore, a low-cost and high-speed color inspection system is needed to examine the output color of a PDP efficiently. It can be realized by a non-contact color inspection system using a cheaper area CCD camera. Though the inspection can be done using RGB signals obtained by a camera, it has been known that the RGB signals have some difficulty to reflect human color sensitivity [2]. Thus, the acquired RGB values should be converted into the XYZ values. There are many existing methods that can directly convert the RGB values into the XYZ values such as those methods cited in [3]. However, the converted XYZ values obtained by these methods are much deviated from those measured by a colorimeter. Thus, a color conversion method in a camera-based system is needed to convert the RGB values into the XYZ values that can be directly compared to the measured values of a colorimeter used as a reference for reliable color evaluation. For this, the conventional color conversion methods including the least square method [2] for inspecting printed materials, the analytic method [3] for enhancing the color fidelity of a CRT, and the numerical method using Taylor series [4] for CRT inspection had been developed.

In this letter, the current study proposes a color conversion method that can analytically calculate the RGB-to-XYZ conversion matrix for a camera-based PDP color inspection. The proposed RGB (camera)-to-XYZ (colorimeter) conversion matrix is constructed by manipulating analytically the inter-related color conversion matrices: the RGB (PDP)-to-RGB (camera), the RGB (camera)-to-XYZ (intermediate), and the RGB (PDP)-to-XYZ (colorimeter) matrices. Thus, this step requires only the measurements of the RGB primaries and the reference white. It is possible that the conventional least square method estimates directly the elements of a RGB (camera)-to-XYZ (colorimeter) conversion matrix. For reducing considerably the color difference between the converted XYZ values and the measured XYZ values, it is found that the least square method requires more data than the proposed method.

2. Camera-Based PDP Color Inspection

The inspection scheme with the proposed color conversion method is shown in Fig. 1. The 42-inch commercial PDP, the color pattern generator, the PC, A101fc made by Basler as an area color CCD camera, and the Color Analyzer CA-100 made by Minolta as a colorimeter were used for this experiment. A test color created by the pattern generator is displayed on the PDP. The colorimeter measures the chromaticity coordinates of the test color in an off-line phase. Simultaneously, the color image is obtained by the area color CCD camera. The PC computes the chromaticity coordinates from the color image and then constructs the color conversion matrix.

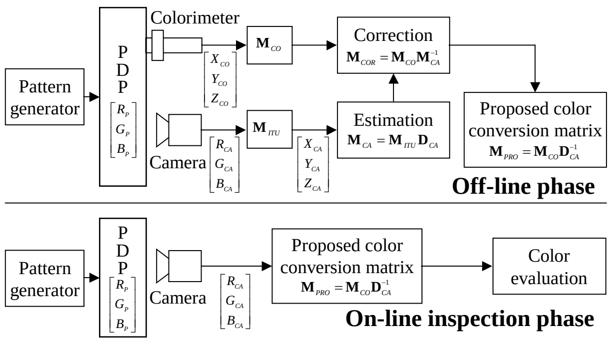


Figure 1. Inspection scheme with proposed color conversion method.

2.1 Proposed Color Conversion Method for PDP Color Inspection

The camera-based PDP color inspection system is divided into two steps. The first step is the off-line phase to obtain the proposed color conversion matrix. The second step is the on-line inspection phase in which the proposed color conversion matrix is applied to the output of the camera-based inspection system, leading to the acquirement of the converted tristimulus values.

The off-line phase uses the camera-based and the colorimeter-based systems to construct the proposed color conversion matrix. The area color CCD camera acquires the color images of the red, green, blue, and white test colors displayed on the PDP. Now, the proposed RGB (camera)-to-XYZ (colorimeter) conversion matrix is constructed by manipulating analytically the interrelated color conversion matrices: the RGB (PDP)-to-RGB (camera), the RGB (camera)-to-XYZ (intermediate), and the RGB (PDP)-to-XYZ (colorimeter) matrices. Let (R_P, G_P, B_P) and (X_{CO}, Y_{CO}, Z_{CO}) be the output RGB values of the PDP and the XYZ values measured by the colorimeter, respectively. Then, the relationship between (R_P, G_P, B_P) and (X_{CO}, Y_{CO}, Z_{CO}) can be specified by the 3×3 color conversion matrix $\mathbf{M}_{CO}$

$$\begin{pmatrix} X_{CO} & Y_{CO} & Z_{CO} \end{pmatrix}^T = \mathbf{M}_{CO}\begin{pmatrix} R_p & G_p & B_p \end{pmatrix}^T. \qquad (1)$$

Hence the matrix $\mathbf{M}_{CO}$ is calculated by using the conventional color conversion method given in [3] as follows: Let the (x, y) chromaticity coordinates of the R, G, and B primaries be (x_r, y_r, z_r), (x_g, y_g, z_g), and (x_b, y_b, z_b), respectively. Let the (x_w, y_w, z_w) values be the (x, y) chromaticity coordinates of a reference white. These values are directly measured by the colorimeter. Then, the matrix $\mathbf{M}_{CO}$ becomes

$$\mathbf{M}_{CO} = \mathbf{xC}, \qquad (2)$$

where $\mathbf{x} = \begin{bmatrix} x_r & x_g & x_b \\ y_r & y_g & y_b \\ z_r & z_g & z_b \end{bmatrix}$, $\mathbf{C} = \begin{bmatrix} C_r & 0 & 0 \\ 0 & C_g & 0 \\ 0 & 0 & C_b \end{bmatrix}$, and $\begin{pmatrix} C_r & C_g & C_b \end{pmatrix}^T = \frac{1}{y_w}\mathbf{x}^{-1}\begin{pmatrix} x_w & y_w & z_w \end{pmatrix}^T$.

Next, consider the interrelated color conversion matrices of the camera. Let (R_{CA}, G_{CA}, B_{CA}) and (X_{CA}, Y_{CA}, Z_{CA}) be the RGB values obtained by the camera and the converted XYZ values corresponding (R_{CA}, G_{CA}, B_{CA}), respectively. Here, the (R_{CA}, G_{CA}, B_{CA}) values use the average RGB values of the central 100×100 pixels of the color image acquired by the camera. Then, the relationship between (R_P, G_P, B_P) and (R_{CA}, G_{CA}, B_{CA}) can be represented by

$$\begin{pmatrix} R_{CA} & G_{CA} & B_{CA} \end{pmatrix}^T = \mathbf{D}_{CA}\begin{pmatrix} R_P & G_P & B_P \end{pmatrix}^T, \qquad (3)$$

where the matrix $\mathbf{D}_{CA}$ is the 3×3 matrix reflecting an environmental distortion. By introducing the known 3×3 color conversion matrix $\mathbf{M}_{ITU}$ with the ITU-R BT.709 primaries and the reference white (D_{65}) chromaticity coordinates given in [5], the relationship between (R_{CA}, G_{CA}, B_{CA}) and (X_{CA}, Y_{CA}, Z_{CA}) can be defined as

$$\begin{pmatrix} X_{CA} & Y_{CA} & Z_{CA} \end{pmatrix}^T = \mathbf{M}_{ITU}\begin{pmatrix} R_{CA} & G_{CA} & B_{CA} \end{pmatrix}^T. \qquad (4)$$

Now, consider the 3×3 color conversion matrix $\mathbf{M}_{CA}$ specifying the relationship between (R_P, G_P, B_P) and (X_{CA}, Y_{CA}, Z_{CA}). Then it follows that

$$\begin{pmatrix} X_{CA} & Y_{CA} & Z_{CA} \end{pmatrix}^T = \mathbf{M}_{CA}\begin{pmatrix} R_P & G_P & B_P \end{pmatrix}^T. \qquad (5)$$

Here, the matrix $\mathbf{M}_{CA}$ can be computed by using Eq. (2) with the (X_{CA}, Y_{CA}, Z_{CA}) values calculated from Eq. (4). Interestingly, the calculation of the matrix $\mathbf{M}_{CA}$ means the estimation of the matrix $\mathbf{D}_{CA}$ implicitly because $\mathbf{M}_{CA}$ is derived as $\mathbf{M}_{CA} = \mathbf{M}_{ITU}\mathbf{D}_{CA}$ by substituting Eq. (3) into Eq. (4). Thus, a distortion caused by an environmental conditions such as lighting, lenses, camera parameters, etc. can be considered.

However, the converted (X_{CA}, Y_{CA}, Z_{CA}) values calculated from Eq. (5) are much deviated from the (X_{CO}, Y_{CO}, Z_{CO}) values measured by a colorimeter as shown in Fig. 2. This shows the corresponding (u', v') chromaticity coordinates of the (X_{CA}, Y_{CA}, Z_{CA}) with small boxes and the (X_{CO}, Y_{CO}, Z_{CO}) with small black triangles for the RGB primaries, the reference white, and Macbeth colorchecker colors, respectively. Thus, it is quite desirable to minimize the difference between them to reliably inspect the colors displayed on PDP. Accordingly, it can be achieved by introducing the color correction matrix $\mathbf{M}_{COR}$ transforming the (X_{CA}, Y_{CA}, Z_{CA}) values into the (X_{CO}, Y_{CO}, Z_{CO}) values defined as

$$\begin{pmatrix} X_{CO} & Y_{CO} & Z_{CO} \end{pmatrix}^T = \mathbf{M}_{COR} \begin{pmatrix} X_{CA} & Y_{CA} & Z_{CA} \end{pmatrix}^T, \quad (6)$$

where the matrix $\mathbf{M}_{COR}$ is analytically solved by using Eqs. (1) and (5). Therefore, it follows that $\mathbf{M}_{COR} = \mathbf{M}_{CO}\mathbf{M}_{CA}^{-1}$. Let the color conversion matrix $\mathbf{M}_{PRO}$ be the matrix specifying the desired relationship between (R_{CA}, G_{CA}, B_{CA}) and (X_{CO}, Y_{CO}, Z_{CO}). It then follows that

$$\begin{pmatrix} X_{CO} & Y_{CO} & Z_{CO} \end{pmatrix}^T = \mathbf{M}_{PRO} \begin{pmatrix} R_{CA} & G_{CA} & B_{CA} \end{pmatrix}^T. \quad (7)$$

Accordingly, the proposed color conversion matrix $\mathbf{M}_{PRO}$ can be analytically calculated using the relation $\mathbf{M}_{PRO} = \mathbf{M}_{CO}\mathbf{M}_{CA}^{-1}\mathbf{M}_{ITU} = \mathbf{M}_{CO}\mathbf{D}_{CA}^{-1}$ obtained by substituting Eq. (4) into Eq. (6). The proposed color conversion matrix should be reconstructed only if the experimental conditions such as lighting, lens, and camera parameters, etc., are changed. In an on-line inspection phase, by applying the color conversion matrix $\mathbf{M}_{PRO}$ to the RGB values acquired by the camera, they can be successfully matched to the tristimulus values measured by the colorimeter.

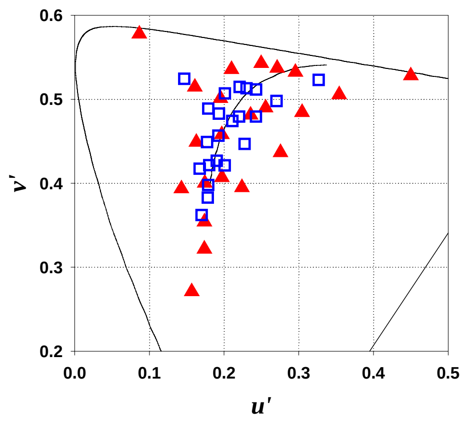
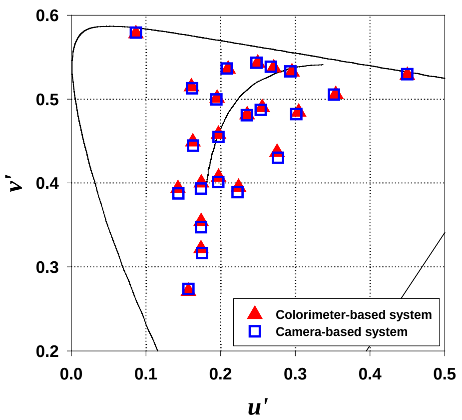


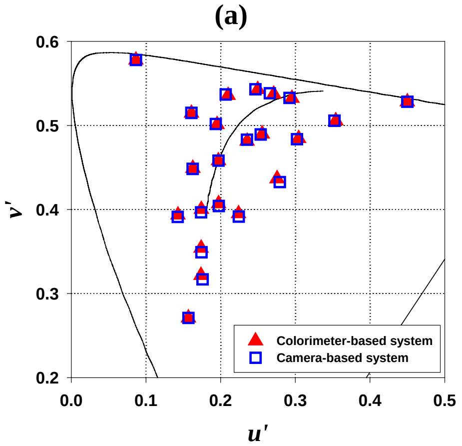
Figure 2. The corresponding (u', v') chromaticity coordinates of the (X_{CA}, Y_{CA}, Z_{CA}) with small boxes and the (X_{CO}, Y_{CO}, Z_{CO}) with small black triangles for the RGB primaries, the reference white, and Macbeth colorchecker colors, respectively.

3. Experimental Results

The current study evaluates the performance of the proposed color conversion by using the color difference $(\Delta u'v')$ between the (u', v') chromaticity coordinates measured by the colorimeter-based system and ones acquired by the camera-based system. According to this criterion, the proposed method was compared to the conventional least square method [2][6] to confirm the effectiveness of the proposed method. The RGB primaries, the reference white, and Macbeth colorchecker colors are put on the (u', v') chromaticity coordinates as shown in Fig. 3. Here, small black triangles represent the (u', v') chromaticity coordinates measured by the colorimeter-based system, while small boxes represent the (u', v') chromaticity coordinates acquired from the camera-based system. Figure 3(a) shows the estimated XYZ values by using the conventional least square method with only the RGB primaries and the reference white. Figure 3(b) shows that the converted XYZ values by using the proposed matrix $\mathbf{M}_{PRO}$ closely approaches to the (X_{CO}, Y_{CO}, Z_{CO}) values measured by the colorimeter. In these Figs. 3(a) and 3(b), the average color differences of the least square method and the proposed method are 0.00367 and 0.00248, respectively. This result shows that the average color difference of the proposed method is smaller than that of the least square method. In a series of experiment, it showed that the least square method required at least 10 different colors sampled evenly on the color gamut to get the accuracy achieved by the proposed method. For a while, two adjacent color patches can usually be distinguished with a $\Delta u'v' \geq 0.004$, but for separated color patches, a shift of $\Delta u'v' \geq 0.04$ is often required to notice a color change [7]. Accordingly, the average color difference of the proposed method is much below the $\Delta u'v' \geq 0.004$ so that a camera-based system adopting the proposed method promises to possibly inspect the output color of a PDP.



(a)



(b)

Figure 3. The corresponding (u', v') chromaticity coordinates of the converted XYZ values by using (a) the least square method and (b) the proposed method for the RGB primaries, the reference white, and Macbeth colorchecker colors.

4. Conclusion

The camera-based system has performed a PDP color inspection by using the area color CCD camera instead of the surface contacting colorimeter. The tristimulus values acquired by the camera-based system are much deviated from the target values measured by the colorimeter-based system. Therefore, this letter proposes the color conversion matrix, which is constructed based on the RGB primaries and the reference white chromaticity coordinates. As a result, the average color difference between the converted XYZ values calculated by the proposed method and the XYZ values measured by a colorimeter is 0.00248, which is much below the threshold of distinguishing two adjacent color patches.

5. Acknowledgements

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6. References

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