Profile connection space for spectral color reproduction

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To improve the color reproduction accuracy of image among digital devices in spectral color reproduction, a novel profile connection space is proposed. The profile connection space is composed of three sets of tristimulus determined by the principal components of typical illuminants and CIE1931XYZ standard colorimetric observer. The spectral reflectance of three common used atlases is transformed to three deformations of the profile connection space, and then transformed back to the spectral reflectance. The color difference between the original and transformed reflectance are very small for the common used illuminants, which indicates that the profile connection space is a good candidate for spectral color reproduction.

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Exact color reproduction among various digital devices is vital in many applications such as archive savings[1], telemedicine, and e-commerce[2]. The metameric color reproduction[3−5] (e.g. ICC) could achieve pleasant reproduction under a controlled environment but fails when the illuminant or observer varies[6]. Spectral color reproduction could relieve these problems and have gotten increasing concerns[7−9], where the spectral profile connection space (PCS) is the critical center of the spectral color reproduction. Tsutsumi *et al.*[10] have proposed the LabPQR PCS for spectral color reproduction. The first three dimensions of LabPQR are CIELAB values under a particular viewing condition, and the additional three dimensions PQR are the reconstructing coefficients corresponding to the principal components of the spectral metameric black reflectance. The LabPQR PCS could represent the spectral reflectance with very high accuracy. However, the PQR coordinates are lack of definitely colorimetric meanings, which increases the difficulty of spectral gamut visualization and the gamut mapping strategy design. In addition, most of the PQR coordinates are small decimals closing to zero, which is inconvenient for construct the look up table in the spectral image reproduction. A novel PCS based on principal components of illuminants is proposed in this letter. The PCS has definitely colorimetric meanings and is compatible well with the widely used ICC color management system. Firstly, the fundamental principle of the new PCS is illustrated, then an experiment is implemented to demonstrate the performance of the PCS.

To save storage space and speed up processing, the spectral reflectance of original object should be transformed to low dimensional PCS in spectral color reproduction. The main objective of spectral color reproduction is to enable color matches under any light source and observer. Therefore the PCS should be a low dimensional color space which could well represent the color information of original object at as many light sources and observer conditions as possible. However, there are various light sources and observers in practice. Fortunately, CIE have defined some illuminants and standard colorimetric observers to represent typical light sources and observers respectively. The CIE A, B, C, D50, D55, D65, D75, the series of fluorescent illuminants $F_i (i = 1, \cdots, 12)$ and CIE1931XYZ standard colorimetric observer were selected to determine the PCS color space in this letter.

Firstly, the spectral radiation intensities of all the illuminants were normalized at 560 nm, then the widely used principal component analysis (PCA)[11] was employed to extract the dominant structure of the illuminants. As the principal components obtained through PCA contain many negative values, which could not be directly used as illuminants, the principal components were linearly transformed to the range of 0–1 through

$$\mathrm{PC}_{\mathrm{normalized}}(\lambda) = \frac{\mathrm{PC}(\lambda) - \mathrm{PC}_{\min}(\lambda)}{\mathrm{PC}_{\max}(\lambda) - \mathrm{PC}_{\min}(\lambda)}, \qquad (1)$$

where $\mathrm{PC}(\lambda)$ and $\mathrm{PC}_{\mathrm{normalized}}(\lambda)$ denote the original and normalized principal components, respectively. $\mathrm{PC}_{\min}(\lambda)$ and $\mathrm{PC}_{\max}(\lambda)$ represent the minimum and maximum elements of principal components, respectively.

The first three transformed principal components PC_1, PC_2, and PC_3 shown in Fig. 1, were chosen as the illuminants of PCS. Then there will be three sets of CIEXYZ tristimulus determined by the three new defined illuminants and the standard colorimetric observer corresponding to each spectral reflectance. All the

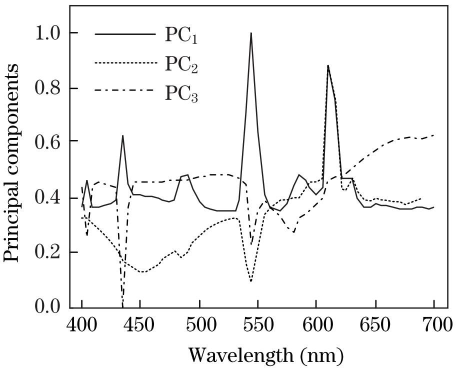

Fig. 1. Linearly transformed three principal components PC_1, PC_2, and PC_3 of CIE and fluorescent illuminants.

three sets of CIEXYZ tristimulus or parts of them formed the PCS proposed in this study.

The spectral reflectance of object could be represented by a vector without a significant loss of accuracy. So for each object with spectral reflectance vector **r**, the corresponding CIEXYZ stimulus values in the PCS could be determined as

$$\begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \\ X_2 \\ Y_2 \\ Z_2 \\ X_3 \\ Y_3 \\ Z_3 \end{bmatrix} = \begin{bmatrix} PC_1(\lambda)\overline{x}(\lambda) \\ PC_1(\lambda)\overline{y}(\lambda) \\ PC_1(\lambda)\overline{z}(\lambda) \\ PC_2(\lambda)\overline{x}(\lambda) \\ PC_2(\lambda)\overline{y}(\lambda) \\ PC_2(\lambda)\overline{z}(\lambda) \\ PC_3(\lambda)\overline{x}(\lambda) \\ PC_3(\lambda)\overline{y}(\lambda) \\ PC_3(\lambda)\overline{z}(\lambda) \end{bmatrix} \mathbf{r}, \tag{2}$$

where the PC_i (i=1, 2, 3) and $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ represent the transformed principal components and CIE1931XYZ standard observer with the same sampling interval as **r**, respectively.

Equation (2) could be rewritten as

$$\mathbf{t} = \mathbf{Mr}, \tag{3}$$

where **t** represents the nine stimulus, **M** denotes the product of the three illuminants and standard observers.

The spectral reflectance **r** could also be described with nine principal components of PCA[11] as

$$\mathbf{r} = \overline{\mathbf{r}} + \mathbf{Va}, \tag{4}$$

where $\overline{\mathbf{r}}$ denotes the mean of the spectral reflectance, **V** represents the nine principal components, and **a** is the coefficient of the corresponding basis vector.

Combining Eqs. (3) and (4) derives

$$\mathbf{a} = (\mathbf{MV})^{-1} (\mathbf{t} - \mathbf{M}\overline{\mathbf{r}}), \tag{5}$$

where '–1' indicates the inverse of matrix.

Inserting Eq. (5) into Eq. (4) gives

$$\mathbf{r} = \overline{\mathbf{r}} + \mathbf{V} (\mathbf{MV})^{-1} (\mathbf{t} - \mathbf{M}\overline{\mathbf{r}}). \tag{6}$$

Then the transformation from spectral reflectance to PCS or reverse could be directly implemented by Eq. (2) or (6) respectively.

The PCS shown above were nine dimension color space, which a little too many for quickly and efficiently spectral color reproduction. As the Y stimulus mainly represents the lightness of the spectral reflectance, and does not contain much colorimetric meanings, hereby the PCS could be further compressed to low dimensions, such as X_1, Y_1, Z_1, X_2, Z_2, X_3, Z_3, with seven dimensions. Three common used atlases, Munsell (1269 chips), NCS (1950 chips), and GretagMacbeth ColorChecker DC (CCDC, central 172 chips, except the 8 glossy chips) were employed to evaluate the performance of the new proposed PCS and transformation methods. The spectrum sampling interval of illuminates and object should be small as the fluorescent illuminants contain much spiky radiance, however, the spectral reflectance of object are represented with 10 nm interval in general. Hereby the nine dimension PCS with 5 and 10 nm sampling interval, the seven dimension PCS with 5 nm sampling interval were all implemented to evaluate the performance of the PCS in different cases.

The spectral reflectance of odd chips from Munsell atlas was employed as training samples to determine the parameters of $\overline{\mathbf{r}}$ and **V**. The spectral reflectance of even chips from Munsell, all the NCS and CCDC chips were used as the three sets of testing samples. Firstly, the measured spectral reflectance of the three sets of testing samples was transformed to the three cases of PCS by Eq. (2) with the corresponding transformed principal components respectively, then transformed back to spectral reflectance. The spectral root mean square errors (RMSE) and CIELAB color difference under illuminate A, D50, D65, F2, F7, F11 between the measured and reconstructed spectral reflectance were calculated, the statistical results are shown in Table 1.

Firstly, it can be seen in Table 1 that the color differences of the three PCSs are very small under all the illuminants, especially for the nine dimension PCS with 5 and 10 nm sampling interval, which indicates that the PCS could achieve accurate color reproduction under the common used illuminants.

Secondly, Table 1 reveals that there are not too much performance difference between the 5 and 10 nm sampling intervals of the nine dimension PCS, the maximum RMSE and color difference under fluorescent illuminants of 10 nm interval even a little smaller than that of 5 nm intervals. This is mainly caused by the fact that the spectral radiances of fluorescent illuminants are smoothed by the 10 nm interval, which is benefit for the PCA to extract the main variances of the illuminants.

Thirdly, the seven dimension PCS performs a little worse than the nine dimension PCS with respect to the color difference. This is mainly due to that the seven dimension PCS loses the two Y stimuli information of the latter two illuminants, which are directly contribute to the color difference. However, the mean color difference of the seven dimension PCS is still very small for all the testing samples and illuminants, in addition, the RMSE of seven dimension PCS is equal to or smaller than that of nine dimension PCS.

Fourthly, it is indicated in Table 1 that all the PCS performed better for Munsell testing samples than that for NCS and CCDC testing samples, which is reasonable. The Munsell testing samples have the same media with the training samples, and the spectral reconstruction accuracy is related with the training and testing media as the media metamerism, so the spectral reconstruction accuracy would be higher when the media of training and testing sample are same. As a whole, all the three PCS performed very well for spectral color reproduction.

In conclusion, a new PCS based on the main structure of the typical illuminants is proposed. Three variants of PCS with different dimensions and sampling intervals are implemented employing the Munsell, NCS, and CCDC atlas as testing samples. The experimental results show that the RMSE and color difference under the common used illuminants are very small for all the three PCSs,

Table 1. Performances of the Three PCS with Different Testing Samples

PCS			Nine Dimension (5 nm)			Nine Dimension (10 nm)			Seven Dimension (5 nm)		
Testing Samples			Munsell	NCS	CCDC	Munsell	NCS	CCDC	Munsell	NCS	CCDC
ΔE^*_{ab}	A	Mean	0.081	0.092	0.108	0.089	0.115	0.136	0.360	0.406	0.572
		Max.	0.670	1.094	0.715	1.246	1.681	1.053	3.062	4.616	3.527
	D50	Mean	0.053	0.051	0.065	0.047	0.049	0.071	0.233	0.272	0.349
		Max.	0.465	0.734	0.272	0.349	0.552	0.313	1.914	2.344	2.669
	D65	Mean	0.058	0.064	0.072	0.062	0.068	0.077	0.303	0.357	0.466
		Max.	0.504	0.755	0.356	0.467	0.689	0.306	2.678	3.029	3.431
	F2	Mean	0.157	0.167	0.197	0.115	0.124	0.151	0.535	0.620	0.776
		Max.	1.634	2.609	0.949	1.000	1.618	0.621	4.648	5.468	6.666
	F7	Mean	0.069	0.077	0.080	0.079	0.087	0.105	0.546	0.633	0.794
		Max.	0.619	0.956	0.334	0.651	0.991	0.429	4.743	5.540	6.769
	F11	Mean	0.141	0.159	0.183	0.104	0.123	0.146	0.531	0.615	0.770
		Max.	1.280	1.806	0.890	0.936	1.413	0.817	4.609	5.435	6.622
RMSE		Mean	0.012	0.017	0.017	0.013	0.017	0.017	0.010	0.015	0.015
		Max.	0.074	0.177	0.105	0.090	0.126	0.088	0.064	0.099	0.061

in addition, the transformation between the spectral reflectance and PCS is unique and quickly, which makes the PCS good candidates in spectral color reproduction.

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