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BRDF rendering by interpolation of optimised model parameters

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Abstract

In this paper, we discuss an interpolation method which can be used to create a look up table to map tristimulus values to BRDF parameters. For a given tristimulus value, we interpolate the XYZ lattice formed by eight primaries and secondaries that were printed and measured, and their corresponding optimised BRDF parameters. The BRDF parameters are obtained by careful optimisation of the Ward model and Cook Torrance model with the BRDF measurements of these primaries. The interpolated BRDF parameters of nine test samples from the same printed samples were then evaluated against the optimised BRDF parameters and their reference BRDF measurements. The results show that, this simple and efficient interpolation method produces consistent BRDF parameters that preserves the diffuse colour of the input sample.

Introduction

Accurate reproduction of the appearance of a scene has always been a goal of colour imaging and it remains a challenge. This requires understanding different components of appearance w.r.t. the human visual system. Colour has been successfully described and measured using defined colour spaces and metrics like colour difference for various viewing conditions and material properties [1]. But to measure colour with gloss and surface geometry, the bidirectional reflectance distribution function (BRDF) must be used.

Adding surface appearance information to colour management will help describe the appearance for different lighting and viewing conditions and give the possibility of connecting different geometries between profiles. Although, there are rendering software applications that can model appearance, there is still the need to include appearance reproduction in colour management in order to implement it during acquisition, production and process control. To do that we need to have a good framework. The first important decision is to choose a BRDF model, use it to fit BRDF parameters, and then find an efficient method that can map tristimulus values to corresponding BRDF parameters.

Previously, we have used optimised BRDF parameters data from Sole et al. [2] and provided a framework using the iccMAX colour management framework that can produce XYZ data at given incidence angle and reflection angle using multiplex connection space [3]. Prior to iccMAX, ICC.1 architecture has been in use for profile creation which is well defined but highly constrained. iccMAX architecture addressed these constraints by making it possible to use connection space other than D50, providing support for spectral data both as an input or as a PCS, making profiles programmable by including calculator element programming, allowing the passing in of environment variables at run time, and allowing the use of directional appearance by providing support for BRDF models and Multiple Connection Space [4]. Given, this flexibility, we implemented a framework where a TIFF file storing the optimised BRDF of the individual samples as input is used to obtain a TIFF file of corresponding tristimulus values with the geometry of any incidence angle/reflection angle provided during runtime while applying the ICC profiles. The Multiplex Connection Space (MCS) was used to implement the framework. Two components of the architecture which provide source data to the MCS are the Multiplex Identification (MID) profile and the Multiplex Visualisation (MVIS) profile [5]. First the MID profile was applied to the TIFF file that identifies the BRDF parameters pixelwise and passes them to the MVIS profile. The BRDF model (in our case the Ward model) was encoded in this MVIS profile that uses the BRDF parameters from the input channels, and the incidence and reflection angles that were provided as variables at runtime. The output is a TIFF file containing tristimulus values at that geometry. This paper is an extension of that preliminary work [3] which is limited to use only the known BRDF parameters and outputs tristimulus for a limited set of samples. In this paper, we explore the possibility of obtaining BRDF parameters from any given 45^o:0^o XYZ (which corresponds to the standard ICC profile connection space, PCS) such that the material connection space profiles can then be applied to create a TIFF file of XYZ at any geometry (incidence angle and reflection angle provided at runtime).

Therefore, the idea is to measure the BRDF of eight possible combinations of CMY inks. The eight samples are the substrate or white(0,0,0), C(100,0,0), M(0,100,0), Y(0,0,100), CM(100,100,0), CY(100,0,100), MY(0,100,100), and CMY(100,100,100) from the FOGRA Media Wedge CMYK V3.0 [6]. These BRDF measurements are used to find the optimised BRDF parameters of each sample using a BRDF model. We then developed an interpolation method that can map 45^o:0^o geometry tristimulus values to BRDF parameters using the 45^o:0^o geometry tristimulus values of the eight primaries and secondaries and their corresponding BRDF parameters. Thus, the objectives of this paper are: (a) to develop a simple and efficient interpolation method to map any 45^o:0^o geometry tristimulus value to BRDF parameters and (b) to use this interpolation method to either create a lookup table that can be encoded in a version 4 ICC profile or to encode the interpolation method in a version 5 (iccMAX) ICC profile.

Method

The BRDF measurements of the eight primaries and secondaries and the nine test samples shown in figure 1 chosen from the FOGRA Media Wedge CMYK V3.0 used in this paper were measured by FOGRA [6]. We then calculated the tristimulus values of eight primaries and secondaries and the test samples at 45^o:0^o geometry using the D65 illuminant and CIE 1964 colour matching functions. (We are considering 0^o:45^o geometry analogous to 45^o:0^o geometry and thus will be using only 45^o:0^o geometry hereafter.) We used the BRDF measurements and Ward BRDF model and Cook Torrance model to fit the BRDF parameters. This gives us the irregular lattice formed by the tristimulus values of the primaries and the secondaries and their corresponding BRDF parameters irregular lattice. We developed an interpolation method that will find the BRDF parameters for any given tristimulus value of 45^o:0^o geometry by interpolating the irregular lattices. For the interpolation method, we have modified the Shepard interpolation method [7] for irregular lattice/space combined with the Neugebauer equations [8] for mixing eight primaries and secondaries. We discuss the method used in detail next.

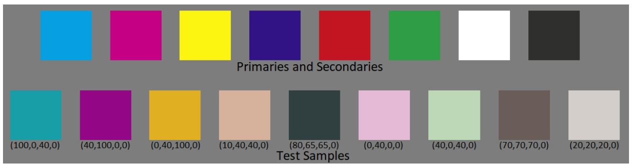

Figure 1. *Eight primaries and secondaries and the nine test samples chosen from the FOGRA Media Wedge CMYK V3.0.*

BRDF Measurements

All the samples were printed on a glossy white paper at FOGRA. The reflectance factor of the eight primaries and secondaries and the nine test samples were measured using GON 360 goniometer equipped with a CAS 140CT array spectrophotometer. The measurements were performed at incidence angles (θ_i) 0°, 15°, 30°, 45° and 60° and viewing angles (θ_r) that varies from 30° to -65° in intervals of 5° w.r.t. incidence angle space.

Ward BRDF

The isotropic and planar Ward BRDF model, in equation 1, gives the relationship between the colorimetric output at a point p, the intensity of the light source at that point p, the illuminant angle, reflection (detector) angle and the BRDF parameters. The specular lobe in this model is assumed to have a Gaussian distribution [9]. For the purpose of this analysis we consider the light source to be a point source and therefore, the incident light intensity will be the same in all direction.

$$I_p(\theta_i;\theta_r) = \begin{bmatrix} I_{pX} \\ I_{pY} \\ I_{pZ} \end{bmatrix} = I_i \cos\theta_i \left(\begin{bmatrix} R_{dX} \\ R_{dY} \\ R_{dZ} \end{bmatrix} \frac{1}{\pi} + \frac{k_S}{\sqrt{\cos\theta_i \cos\theta_r}} \frac{e^{[-\tan^2\delta/m^2]}}{4\pi m^2} \right) \quad (1)$$

I_p is the tristimulus value at point P with incident angle θ_i and reflection angle θ_r. I_i is the incident light intensity, R_{dx}, R_{dy} *and* R_{dz} are the spectral diffuse reflectance components, k_s is the specular coefficient of the sample and $\delta = (\theta_i - \theta_r)/2$ at point P.

Cook Torrance BRDF

The Cook Torrance BRDF is a physically based BRDF model based on the idea that only those microfacets oriented towards the H vector contribute to the final reflection at angle θ_i as show in figure 2 [10].

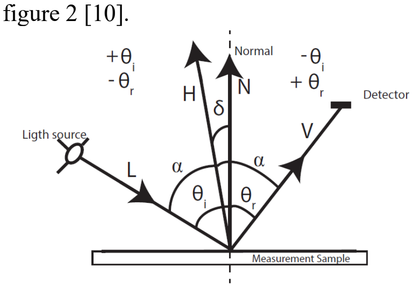

Figure 2. *Angles and vectors used in the BRDF equations [10].*

The specular term R_s in this case is the compound of the functions D, F and G as shown in equation 2, where D is the microfacets distribution, F is the Fresnel factor that is reflected from the entire surface with angle α between the H vector and the reflected light direction as shown in figure 2, and G is the geometric attenuation factor (i.e. light that is not accounted for due to shadowing and masking) as shown in equation 3. D is typically a Gaussian distribution and, in this case, we use the Beckmann distribution as shown equation 4 [11] and F is considered to be 1.

$$R_s = \frac{FDG}{\pi(\mathbf{n}\cdot\mathbf{l})(\mathbf{n}\cdot\mathbf{v})} \quad (2)$$

$$G = \min\left\{1, \frac{2(\mathbf{n}\cdot\mathbf{h})(\mathbf{n}\cdot\mathbf{v})}{(\mathbf{v}\cdot\mathbf{h})}, \frac{2(\mathbf{n}\cdot\mathbf{h})(\mathbf{n}\cdot\mathbf{l})}{(\mathbf{v}\cdot\mathbf{h})}\right\} \quad (3)$$

$$D = \frac{1}{m^2\cos^4\delta} e^{-[(\tan\delta)/m]^2} \quad (4)$$

The simplified isotropic Cook Torrance BRDF model used in this paper is given in equation 5. For each primary and secondary sample, the tristimulus values calculated using the measured reflectance data, D65 illuminant and CIE 1964 colour matching functions are then used to fit and optimise the BRDF parameters k_s, R_{dx}, R_{dY}, R_{dz} and m using the Nelder-Mead downhill simplex algorithm [12] and ΔE_{00} colour difference as the objective function [2] i.e. the ΔE_{00} between the measured and estimated tristimulus values was minimized.

$$I_P = \begin{bmatrix} I_{P_X} \\ I_{P_Y} \\ I_{P_Z} \end{bmatrix} = I_{ia}R_a + I_i\cos\theta_i\left(k_sR_s + (1-k_s)\begin{bmatrix} R_{d_X} \\ R_{d_Y} \\ R_{d_Z} \end{bmatrix}\right) \quad (5)$$

I_p is the tristimulus value at point P with incident angle θ_i and reflection angle θ_r. I_i is the incident light intensity, R_{dx}, R_{dy} *and* R_{dz} are the spectral diffuse reflectance components, k_s is the specular coefficient of the sample and $\delta = (\theta_i - \theta_r)/2$ at point P. The term I_aR_a is the ambient light which is assumed to be zero as the experiment was performed in dark conditions. The specular component R_s is already given in equation 2.

Neugebauer model

The Neugebauer model is used to predict spectra or colorimetry of halftoned colour prints. This model states that using the probability of area coverage by cyan, magenta and yellow inks, we can predict any colour formed in between. The probability of area coverage of these ink can be interpreted from the fractional area covered by cyan, magenta and yellow inks [8]. Let these probabilities be c, m and y then the probability of absence of these inks will be *(1-c), (1-m) and (1-y)* respectively. Therefore, the probability of white i.e. the substrate will be *(1-c)(1-m)(1-y).* The probability of pure cyan will be *c(1-m)(1-y)*, or a mix of cyan and magenta but no yellow will be *cm(1-y)* and so on. Therefore, the spectrum or colorimetry can be obtained by mixing respective spectra/colorimetry of the eight primaries and secondaries according to the ink probabilities. This mixing can be obtained using interpolation methods like trilinear interpolation where the CMY primaries and secondaries form a regular lattice mapping to an irregular lattice. The Neugabauer equations can be surmarised as below, where given, X_i, Y_i, Z_i, the tristimulus values of the eight primaries and secondaries and the probabilities c, m and y then the corresponding tristimulus value $(X_{cmy}, Y_{cmy}, Z_{cmy})$ is given by:

$$X_{cmy} = \sum_{i=1}^{8}(w_iX_i), \quad Y_{cmy} = \sum_{i=1}^{8}(w_iY_i), \quad Z_{cmy} = \sum_{i=1}^{8}(w_iZ_i)$$

where,

$$w_i = [(1-c)(1-m)(1-y),\ c(1-m)(1-y),\ (1-c)m(1-y),\ (1-c)(1-m)y,\ cm(1-y),\ c(1-m)y,\ (1-c)my,\ cmy]$$

Shepard Interpolation

The Shepard interpolation is useful in interpolating data forming irregular lattice or scattered points [7]. It is a simple form of inverse distance weighted interpolation. Let there be a set of n scattered data points x_i and y_i where $i \in \{1,2,...,n\}$, $x_i \in R^N$ and $y_i \in R^M$. For any point x the corresponding y value can be interpolated by weighting y_i with the inverse distance of x with x_i. Let distance $D_i = ||x - x_i||_p$ where p is the Lp norm and can be chosen accordingly [13]. Then,

$$y = \frac{\sum_i^n y_i D_i^{-\mu}}{\sum_i^n D_i^{-\mu}}.$$

Interpolation Method

An interpolation method has been developed from the Shepard interpolation and Neugebauer model to find the BRDF parameters of a BRDF model for an input tristimulus value of 45º:0º geometry. This is done by mixing the 45º:0º geometry tristimulus values of the eight primaries and secondaries and their corresponding BRDF parameters obtained using the BRDF model. This algorithm is a modification to the Shepard interpolation with inspiration from the Neugebauer model to mix eight secondaries and primaries but in an irregular space. The modification is done to preserve the chromaticity of the input first, by sorting the primaries and secondaries according to the closest chromaticity to the input. The top closest group of primaries and secondaries in chromaticity is chosen such that the inverse distance interpolation of the tristimulus values of this group of primaries and secondaries produces the least colour difference with the input. This helps in choosing the optimal number of primaries and secondaries required to mix. Once the closest interpolated tristimulus value and its corresponding BRDF parameters are obtained then the diffuse components of the interpolated BRDF parameters are scaled with individual factors such that these factors scale the interpolated tristimulus value to the input tristimulus value. The specular coefficient and the standard deviation obtained by the distance weighted interpolation then describes the specular lobe. The algorithm is described below.

Let the input tristimulus value be the vector I, and the tristimulus values of the eight primaries and secondaries be the vectors I_i and their corresponding BRDF parameters be the vectors B_i where $i \in \{1,2,3,...,8\}$ and $B_i \in R^5$.

Calculate the chromaticity co-ordinates vector C of I and the chromaticity co-ordinates vectors C_i of I_i respectively, where $i \in \{1,2,3,...,8\}$.

For a given tristimulus value the chromaticity co-ordinates x, y, z are given by:

$$x = X/(X+Y+Z);\ y = Y/(X+Y+Z);\ z = Z/(X+Y+Z);$$

Find the distance between vectors C and C_i, based on L_p norm as follows:

$$d_i = ||C - C_i||_p,$$

where p can be chosen accordingly, in this case we have chosen $p = 2$ which reduces it to Euclidean distance.

Create vectors S_i that store the index i of d_i in ascending order of distance values in vector d_i, i changes from 1 to 8.

Set $n = 1$ and do the following:

a Set colour difference variable $E = 1000$.

b Calculate distance $D_i = || I - I_{S_i}||$, where i changes from 1 to n.

c Calculate tristimulus value T' as:

$$T' = \frac{\sum_i^n I_{S_i} D_i^{-\mu}}{\sum_i^n D_i^{-\mu}},$$

where, μ can be chosen accordingly. In this case, we have chosen $\mu=1$.

c.d Calculate the colour difference E' using ΔE_{00} between T' and I.

c.e If $E' < E$, then set $E = E'$, interpolated tristimulus vector $T = T'$, and calculate interpolated BRDF parameters vector B as:

$$B = \frac{\sum_i^n B_{S_i} D_i^{-\mu}}{\sum_i^n D_i^{-\mu}},$$

c.f Increment n and continue step b. to step f. until $n = 8$.

Once we have the closest tristimulus value T and its corresponding BRDF parameters B, then we need to scale each tristimulus co-ordinates (T_x,T_y,T_z) of T to the tristimulus co-ordinates (I_x,I_y,I_z) of I and apply the same individual scaling to the diffuse components (R_x,R_y,R_z) of B respectively:

$$a = I_X/T_X, \quad b = I_Y/T_Y, \quad \text{and} \quad c = I_Z/T_Z,$$

By scaling with a, b and c we get $T = (I_X, I_Y, I_Z)$ and the diffuse components of $B = (aR_X, bR_Y, cR_Z)$. This ensures that the input colour is preserved. It is possible because the diffuse components and the input tristimulus value share a relationship, and multiplying, both T and the diffuse components of B by the same ratios we still maintain the same relationship between the two.

Results and Discussion

The tristimulus values and the optimised BRDF parameters were calculated for white, C, M, Y, CM, CY, MY and CMY samples for the Ward and Cook Torrance BRDF models. Using these optimised BRDF parameters and their corresponding BRDF equation i.e. equation 1 or equation 5, the tristimulus values were calculated for the five incidence angles 0º, 15º, 30º, 45º and 60º (θ_i space) and reflection angles -30º to 65º (θ_r space) in intervals of 5º. ΔE_{00} is calculated between these values and the corresponding tristimulus values obtained using the measured reflectance data. The overall mean ΔE_{00} was 6.79 (Ward BRDF), 6.5 (Cook Torrance BRDF) for the eight primary and secondary samples. The specular peaks of the measured data in terms of Y (relative luminance) cd/m^2 increases with increasing angle of incidence. It should be noted that the tristimulus values of diffuse reflection obtained using the two models are scaled by $cos(\theta_i)$ which decreases the overall brightness value as the incidence angle increases. The BRDF parameters obtained from the Ward model create specular peaks such that the scaling reverses the relationship of relative luminance with respect to the increase in incidence angle i.e. peak Y values decrease accordingly. This overall decrease in brightness as the incidence angles increases also occur in the case of the Cook Torrance model while the specular peaks still hold the same relationship after scaling as in the case of the reference BRDF measurements. The root mean square differences (RMSD) between the Y values of the reference specular highlights and the specular highlights obtained from the optimised BRDF parameters of the primaries and secondaries were also calculated. Figure 3a shows the relative luminance plot of the primary sample (yellow) with the highest RMSD i.e. 1.20x10^2 cd/m^2 in the case of Cook Torrance model. Figure 3b shows the relative luminance plot of the sample (cyan) with the highest RMSD i.e. 1.40 x10^{2}cd/m^2 in the case of Ward model, respectively.

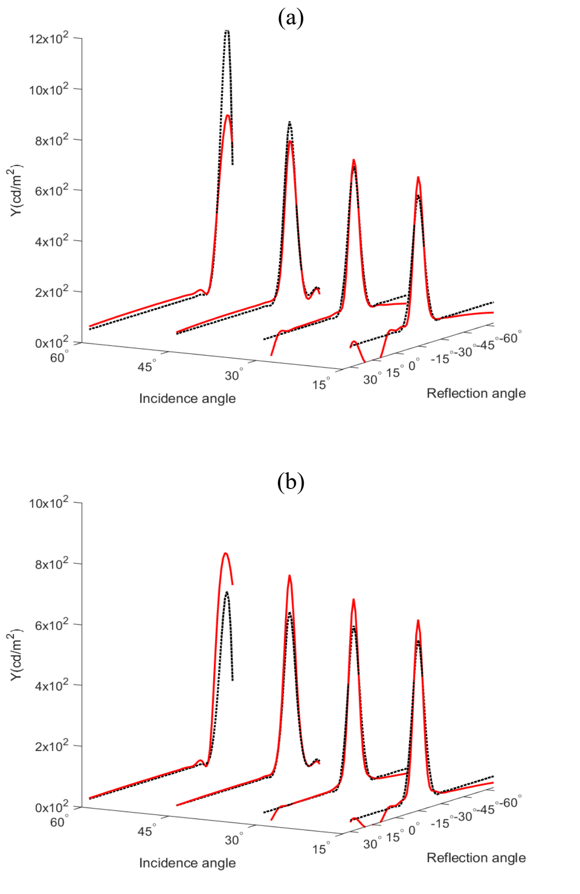

Figure 3. *The Y values obtained from measured BRDF (red line) and optimised BRDF (black dotted line) parameters are plotted against the reflection angles for each incidence angle. Plot (a) is of primary Yellow which has the highest RMSD in Y for Cook Torrance model. Plot (b) is of secondary Cyan which has the highest RMSD in Y for Ward model.*

The plot in figure 3a, shows that the specular peaks obtained from the Cook Torrance model at incidence angle 30º 15º and 45º are close to the measured specular peaks, while for 60º incidence angle the specular peak is overestimated. In the case of the Ward Model, figure 3b shows that the specular peaks obtained are underestimated for all the incidence angles; however, as the incidence angles decrease the difference between the measured and the estimated specular peaks decreases. We will use these optimised BRDF parameters for our interpolation method.

The main objective in this paper is to derive an interpolation method and evaluate it by comparing the BRDF parameters output to the optimised BRDF parameters and the reference BRDF measurements. Given the results shown above, the BRDF parameters obtained from our interpolation method can be seen to lie within the accuracy obtained by the optimised parameters. (We limited our evaluation to the incidence and reflection angles used in the optimisation model in order to maintain reliability.)

Another observation is that, for tristimulus values around the specular peak, the Y (relative luminance) value goes above 100 cd/m^2. The $J_z a_z b_z$ colour difference [14] was considered as the objective function but as it is designed for high dynamic range data, the colour differences obtained were very low which required the optimisation tolerance value to be reduced substantially. The optimised BRDF parameters thus obtained were not significantly better than the parameters obtained using ΔE_{00} as the objective function. For this reason, we chose to use ΔE_{00} as the objective function.

The interpolation method was applied to nine test samples that have black value K = 0 from the FOGRA media wedge shown in figure 1 and evaluated for both Ward and Cook Torrance models. The reference BRDF measurements and the optimised BRDF parameters were obtained for these nine samples to evaluate the performance of the interpolated BRDF parameters. The root mean square differences (RMSD) between the interpolated BRDF and the optimised BRDF parameters were calculated. For illustration purposes, the samples with 50th percentile and maximum of RMSD obtained using the Cook Torrance model are shown in figures 5 and 6, respectively, as sRGB representations. Figure 7 and 8 are sRGB representations of samples for which the RMSD between the interpolated BRDF and the optimised BRDF parameters using the Ward model is 50th percentile and the highest, respectively. The black patches depict reflection angles at which the measurements were not possible when measuring the BRDF.

Figures 4a and 4b show the relative luminance obtained from the measured BRDF, optimised BRDF and interpolated BRDF parameters, plotted against reflection angles of samples with 50th percentile and maximum of RMSD obtained using the Cook Torrance model. Figure 9a and 9b show the relative luminance against reflection angles plotted for the four incidence angles of samples with 50th percentile and maximum of RMSD using the Ward model. The red solid line, dotted line and dashed line correspond to relative luminance values obtained from reference BRDF measurements, optimised BRDF parameters and the interpolated BRDF parameters respectively. The specular peaks obtained using interpolated method as seen in these plots follow the same characteristics found in the case of optimised BRDF of the primaries and secondaries discussed earlier.

We also calculated the average RMSD between the Y values obtained using interpolated BRDF parameters and reference Y values at specular highlights, and between Y values obtained from optimised BRDF parameters and reference Y values at specular highlights for each incidence angle for all the nine test samples as shown in table 1.

Table 1: Average RMSD of the nine test samples between the Y values obtained using interpolated BRDF parameters & reference Y values and RMSD between the Y values obtained using optimised BRDF parameters & reference Y values at specular highlights.

		15º	30º	45º	60º
Interpolated BRDF parameters & reference BRDF measurements	CT	0.48	0.37	0.66	2.24
	Ward	0.72	0.57	0.62	2.03
Optimised BRDF parameters & reference BRDF measurements	CT	0.82	0.66	0.54	1.61
	Ward	0.70	0.58	0.68	2.07

From the table we can see, that in the case of Cook Torrance model the predicted Y values are close to the reference Y values at incidence angles 30º, 45º and 15º. For incidence angle 60º the Y values are overestimated at the specular peak with an RMSD of above 2 i.e. around 200 cd/m^2. The Y values of the specular peak obtained from interpolated BRDF parameters overestimates specular peaks more than the specular peaks from optimised BRDF parameters at 60º incidence angle.

In the case of Ward model, the Y values of specular highlights obtained using interpolated BRDF parameters are close to the Y values obtained using reference BRDF at incidence angles 30º, 45º and 15º. The RMSD of Y value is 2.03

i.e. around 203 cd/m^2 at incidence angle 60º. Results from the interpolated BRDF parameters and optimised BRDF parameters are similar in this case.

Estimation of specular peaks using interpolated BRDF remain consistent for all the samples. The Y values obtained using optimised BRDF parameters are not as consistent and close to the reference for all the samples. Specular peaks predicted using optimised BRDF parameters might suffer due to local minima.

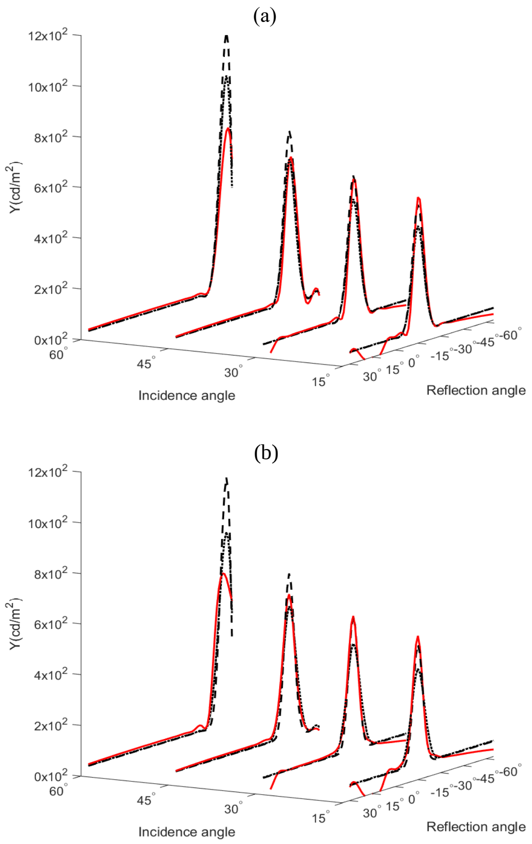

Figure 4. (a) is the plot for relative luminance Y that corresponds to test sample with 50th percentile of RMSD, (b) is the plot for relative luminance Y that corresponds to test sample with the maximum of RMSD obtained between interpolated BRDF parameters and optimised BRDF parameters for Cook Torrance model. Red solid line depicts BRDF measurements, dotted line depicts optimised BRDF parameters and dashed line depicts interpolated BRDF parameters.

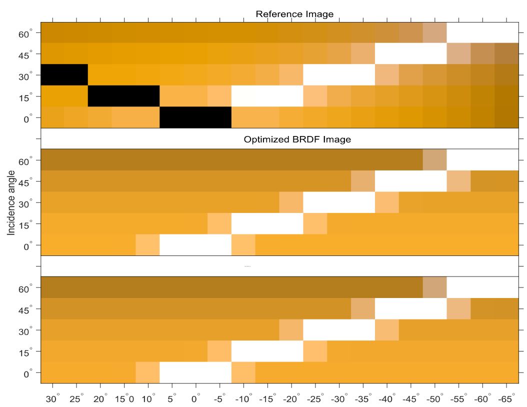

Figure 5. This figure corresponds to colorimetric representation of the reference BRDF measurements (top), optimised BRDF parameters (middle) and the interpolated BRDF parameters (bottom) of the sample that is 50th percentile of RMSD between interpolated BRDF parameters and optimised BRDF parameters for Cook Torrance model.

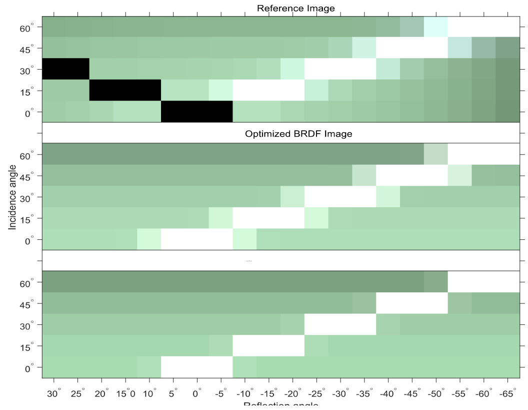

Figure 6. This figure corresponds to colorimetric representation of the reference BRDF measurements (top), optimised BRDF parameters (middle) and the interpolated BRDF parameters (bottom) of the sample that had maximum of RMSD between interpolated BRDF parameters and optimised BRDF parameters for Cook Torrance model.

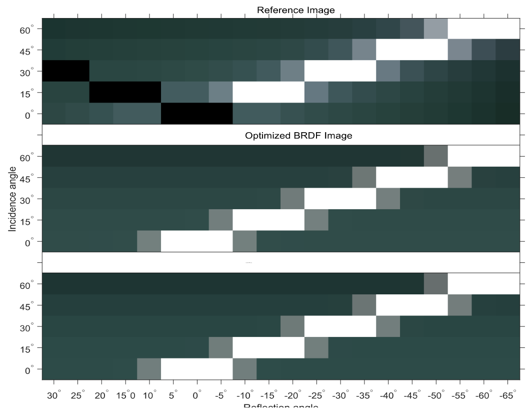

Figure 7. This figure corresponds to colorimetric representation of the reference BRDF measurements (top), optimised BRDF parameters (middle) and the interpolated BRDF parameters (bottom) of the sample that is 50th percentile of RMSD between interpolated BRDF parameters and optimised BRDF parameters for Ward model.

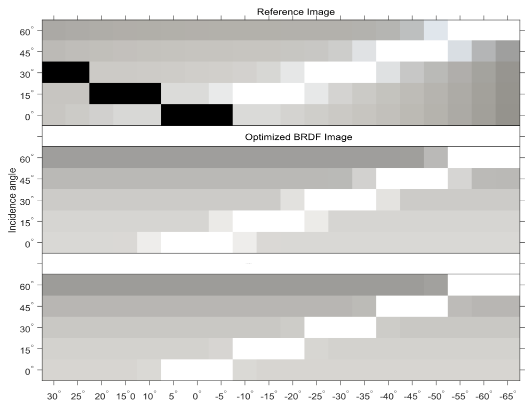

Figure 8. This figure corresponds to colorimetric representation of the reference BRDF measurements (top), optimised BRDF parameters (middle) and the interpolated BRDF parameters (bottom) of the sample that is maximum of RMSD between interpolated BRDF parameters and optimised BRDF parameters for Ward model.

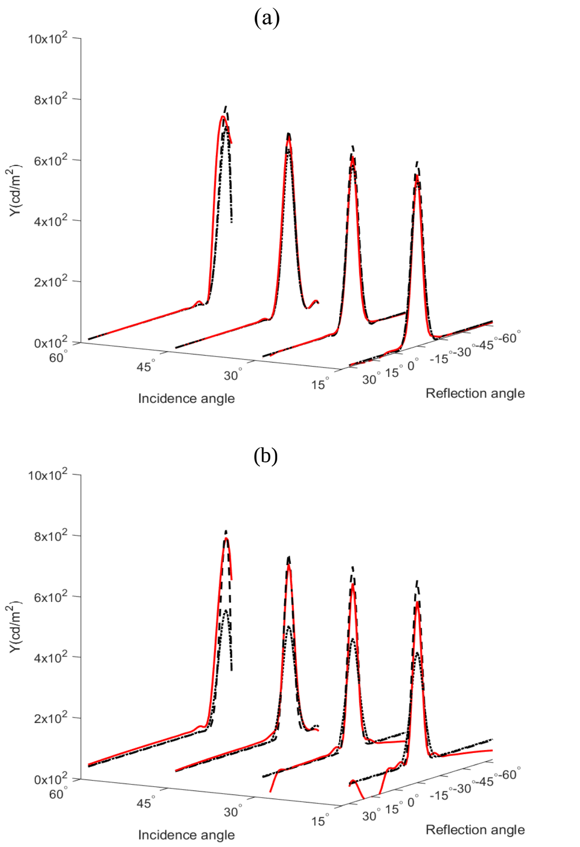

Figure 9. *(a) is the plot for relative luminance Y that corresponds to test sample with 50th percentile of RMSD, (b) is the plot for relative luminance Y that corresponds to test sample with the maximum of RMSD obtained between interpolated BRDF parameters and optimised BRDF parameters for Ward model. Red solid line depicts BRDF measurements, dotted line depicts optimised BRDF parameters and dashed line depicts interpolated BRDF parameters.*

Table 2 shows the average ΔE_{00} of diffuse reflections calculated between tristimulus values obtained using interpolated BRDF parameters, reference BRDF measurements and optimised BRDF for all the test samples. The average ΔE_{00} between the interpolated and optimised BRDF is close to 1. The overall colour difference obtained between the two BRDF models is similar. This shows that once BRDF parameters of the primaries and secondaries are carefully obtained then mixing these vertices using the interpolation method can retain the BRDF characteristics contributed by the optimised BRDF parameters of the primaries and secondaries and the input sample's diffuse colour. Since to obtain optimised BRDF parameters, the tolerance value, training data, initial parameters, optimisation method etc. must be properly chosen and tested for each sample every time, this interpolation method is a more reliable and efficient method to predict BRDF for a large number of samples.

Figure 10a shows, that for all nine test samples the chromaticity of diffuse reflection is preserved by interpolated BRDF parameters (white asterisks) and optimised BRDF (red dots) parameters and are as close to the chromaticity obtained from the reference BRDF measurements (black circles). Figure 10b shows that for all the nine test samples the chromaticity at specular reflection is close to D65 (black circle) for interpolated BRDF parameters (white asterisks) and optimised BRDF (red dots) parameters while the average chromaticity obtained from reference BRDF measurements (black dots) is (0.2789, 0.2908).

Table 2: Average colour difference of diffuse reflection of all test samples calculated between tristimulus values obtained from interpolated BRDF parameters, reference BRDF measurements and optimised BRDF parameters for Cook Torrance and Ward Model.

	CT ΔE(diffuse)	Ward ΔE(diffuse)
Interpolated BRDF parameters/ reference BRDF measurements	5.02	5.09
Optimised BRDF parameters/ reference BRDF measurements	4.74	4.85
Optimised BRDF parameters/ Interpolated BRDF measurements	1.17	1.11

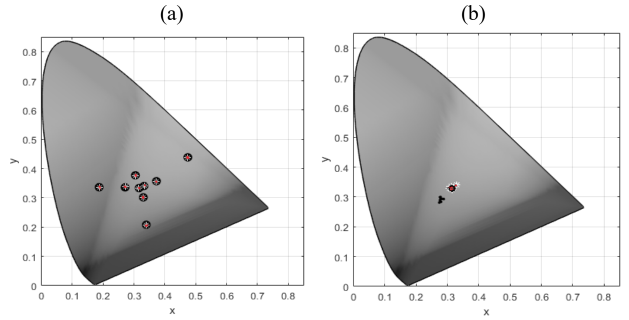

Figure 10. *Mean chromaticity obtained from the optimised BRDF parameters, interpolated BRDF parameters and reference BRDF measurements for all the nine-test sample. (a) Chromaticity of diffuse reflections (b) Chromaticity of specular reflections plotted for measured BRDF (black circles), optimised BRFD (red dots) add interpolated BRDF (white asterisks).*

Conclusions

From the results it is seen that the interpolated BRDF parameters remain consistent when used to derive the tristimulus values and the specular lobe w.r.t incidence angles. The interpolation method is able to predict the specular co-efficient k_s and standard deviation m reasonably well. When using the reference BRDF measurements, the fitted k_s and m values were quite similar among the primaries and secondaries. While the prediction has preserved the diffuse colour and obtained an acceptable specular peak for 45º, 30º and 15º incidence angle, the relative luminance difference increases for the 60º incidence angle, which is a limitation of the BRDF optimisation. The Cook Torrance model was able to predict the specular peaks' relationship to incidence angle seen in the reference BRDF measurements for all the samples, better than the Ward model. The interpolated BRDF parameters were also able to preserve these relationships. The chromaticity at diffuse reflection is preserved for all the samples while there is a shift in chromaticity at the specular highlights and as expected is closer to the chromaticity of the illumination used.

Other BRDF models such as Lafortune BRDF and Strauss BRDF should also be tested to see the performance of the interpolation method for different types of BRDF models. With an improved model and well optimised BRDF parameters for the primaries and secondaries, the interpolation method is expected to be able to predict parameters accurately for different incidence angles. Further, it is important to evaluate the interpolation method for samples with more complex surface properties. Due to its simplicity and efficiency this interpolation can be integrated into colour management as a lookup table in ICC version 4 or the method can be encoded using ICC version 5. These profiles that map XYZ to BRDF parameters along with the previous work [3] done to obtain XYZ for a given geometry by applying ICC profile to the BRDF parameters in a TIFF file defines a complete framework to map tristimulus values from 45º:0º geometry (PCS) to tristimulus values at another geometry.

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