BEYOND THE NEUTRAL INTERFACE REFLECTION ASSUMPTION IN ILLUMINANT COLOR ESTIMATION

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ABSTRACT

The neutral interface reflection (NIR) assumption is a widely accepted theory in computer vision. According to the NIR the color of specularities of dielectric materials is the color of the incident illumination and the influence of the Fresnel reflectance is neglected. We show, that there is a material- and geometry-dependent shift between the color of the specularity and the color of the incident light due to the Fresnel effect which for human skin can be up to approximately 5.8%. As the NIR concept is often the core idea of specularity-based illuminant-color estimation techniques, the ignored Fresnel effect introduces a systematic error in the estimation result. We thus propose a material-dependent rectification method for correcting this color shift. Our experiments on human skin regions show an average improvement of the illuminant color estimation of about 30%.

***Index Terms*—** Neutral interface reflection, Fresnel reflectance, Cook-Torrance reflection model, illumination estimation.

1. INTRODUCTION

The majority of surfaces in natural scenes exhibit both diffuse and specular reflectance. One advantage of diffuse reflectance is that the color of the reflected light and its geometry-dependent intensity are separable for most materials. However, in specular highlights, these two attributes of the reflected light depend on both the geometry of the scene and the index of refraction of the material, which is a function of wavelength. The physically-based model by Cook and Torrance [1] is a good approach for modeling the directional and spectral composition of highlights. The wavelength-dependency in this model is captured by the Fresnel term.

As the refractive indices of dielectric materials often vary only insignificantly with wavelength, it is assumed that their specular reflectance can also be considered to be almost constant over wavelength. Consequently, the color of specularities is assumed to be the color of the incident illumination. This hypothesis is known as the neutral interface reflection (NIR) assumption and is widely used in computer vision applications (e.g. [2, 3, 4, 5]). In the field of illuminant color estimation there exists a group of techniques which exploit the specular reflections in images (e.g. [6, 7, 8, 9]). The core idea of all these methods is the neutral interface reflection assumption. By finding specularities in the scene and determining their color, an estimate of the illuminant color is extracted.

However, previous analysis on multispectral data (and under laboratory conditions) has shown that even for dielectric materials the effects of the wavelength-dependent variation of the refractive indices on the Fresnel reflectance is not negligible [10]. We show that even in RGB space for materials like skin, the color shift in the color of specularities due to the Fresnel term is significant and can thus negatively influence illuminant color estimation. Therefore, we also propose a method to correct the Fresnel effect in specularity-based illumination estimation. The correction of the color shift is material-dependent. Experiments on skin-regions on real images show that the rectification can enhance the illuminant estimation performance up to approximately 30%.

2. NEUTRAL INTERFACE REFLECTION

The surfaces of most materials exhibit a mixture of diffuse and specular reflectance. By using the dichromatic reflection model [2] the reflected light can be expressed as:

$$\begin{aligned} I(\mathbf{x}, \lambda) = \quad & w_d(\mathbf{x}) S_d(\mathbf{x}, \lambda) E(\mathbf{x}, \lambda) \\ + \quad & w_s(\mathbf{x}) S_s(\mathbf{x}, \lambda) E(\mathbf{x}, \lambda) \end{aligned} \tag{1}$$

The model states that the reflected light $I(\mathbf{x}, \lambda)$ of a certain wavelength λ and at an image position $\mathbf{x}$ is the linear combination of two independent parts: the diffuse and the specular reflections. They, in turn, depend on geometric parameters $w_d(\mathbf{x})$ and $w_s(\mathbf{x})$, the diffuse reflectance function $S_d(\mathbf{x}, \lambda)$, the specular reflectance function $S_s(\mathbf{x}, \lambda)$, and the spectral energy distribution function of the illumination $E(\mathbf{x}, \lambda)$.

According to the dichromatic reflection model, the spectral reflectance functions $S_d(\mathbf{x}, \lambda)$ and $S_s(\mathbf{x}, \lambda)$ only depend on the wavelength at a certain position, but are independent of geometry. The geometrical parameters $w_d(\mathbf{x})$ and $w_s(\mathbf{x})$ are geometrical scaling factors depending only on geometry at a certain position but independent of wavelength.

Two widely used assumptions in computer vision and illuminant color estimation are: a) the color of the illuminant is constant across the scene (e.g. [4, 6, 7, 8]), b) the color of the specular reflection can be apporximated by the color of the incident light (also known as the NIR assumption, e.g. [4, 6, 7, 8]). Under these two assumptions Eq. 1 becomes:

$$I(\mathbf{x}, \lambda) = w_d(\mathbf{x}) S_d(\mathbf{x}, \lambda) E(\lambda) + w_s(\mathbf{x}) E(\lambda). \tag{2}$$

3. THE FRESNEL EFFECT ON ILLUMINANT ESTIMATION

In order to understand the impact of the neutral interface reflection assumption it is necessary to closely examine the formation of specular reflectance. Compared to diffuse reflectance, modeling specular highlights is more complex, as the color of the specularity depends on the angle of incidence of the light on the surface and the refractive indices of the materials at the surface of the object. The refractive indices depend on wavelength. Furthermore, unlike diffuse reflection, the impact of wavelength and geometry are not separable.

The Cook and Torrance reflectance model [1] is a physically-based model, which predicts both the directional and the spectral distribution of the specularly reflected light. The fraction of the incident light, which is specularly reflected, is defined as

$$w_s(\mathbf{x})S_s(\mathbf{x},\lambda) = \frac{D(\mathbf{x})G(\mathbf{x})F(\mathbf{x},\lambda)}{\pi(N\cdot L)(N\cdot V)}. \tag{3}$$

$D(\mathbf{x})$ is the micro-facet distribution term controlling the influence of the surface roughness. The self-shadowing and -masking of the micro-facets is included in $G(\mathbf{x})$. L is the light direction vector, V is the viewing vector and N is the surface normal. While $D(\mathbf{x})$ and $G(\mathbf{x})$ only describe the geometric interaction of the light with the surface's microfacets, the Fresnel reflectance term $F(\mathbf{x},\lambda)$ defines the amount and the spectral composition of the reflected light . The Fresnel term incorporates the effects of color, material and angle of incidence of the reflected light. It is defined as [11]:

$$F(\theta_i,\lambda) = \frac{1}{2}\left(r_\perp^2(\theta_i,\lambda) + r_\parallel^2(\theta_i,\lambda)\right), \tag{4}$$

where θ_i is the angle of incidence at a position$\mathbf{x}$. The amplitude reflection coefficients $r_\perp$ and $r_\parallel$ depend on the polarization of the incident light (either perpendicular $\perp$ or parallel $\|$) and can be computed as follows

$$r_\perp(\theta_i,\lambda) = \frac{n_i(\lambda)\cos(\theta_i) - n_t(\lambda)\sqrt{1-n_{it}^2(\lambda)\sin^2(\theta_i)}}{n_i(\lambda)\cos(\theta_i) + n_t(\lambda)\sqrt{1-n_{it}^2(\lambda)\sin^2(\theta_i)}}, \tag{5}$$

$$r_\parallel(\theta_i,\lambda) = \frac{n_i(\lambda)\sqrt{1-n_{it}^2(\lambda)\sin^2(\theta_i)} - n_t(\lambda)\cos(\theta_i)}{n_i(\lambda)\sqrt{1-n_{it}^2(\lambda)\sin^2(\theta_i)} + n_t(\lambda)\cos(\theta_i)}, \tag{6}$$

where $n_{it}(\lambda) = \frac{n_i(\lambda)}{n_t(\lambda)}$. The refractive indices $n_i(\lambda)$ and $n_t(\lambda)$ of the incident and the transmitting media are wavelength-dependent.

As the Fresnel reflectance term is a function of the angle of incidence and of the material-dependent refractive indices and subsequently of wavelength, the specular reflectance modeled by Cook and Torrance shows two major characteristics. Firstly, due to material-specific refractive indices, different materials exhibit a different specular reflectance. Secondly, the specular reflectance will vary with wavelength, if the index of refraction of a certain medium varies with wavelength. This implies that the color of the specular reflection differs from the color of the incident light. Dependent on the angle of incidence, the amount of this color shift changes. Fig. 1 shows the Fresnel reflectance term for different refractive indices n_t. Denser materials, having a higher refractive index, have an increased specular reflection, as less light is transmitted through the medium. Furthermore, as the figure shows, that when θ_i approaches $90°$ the color of the highlight approaches the color of the incident light, since the Fresnel term approaches unity. Thus, the color shift of the highlight away from the light source color, introduced by the Fresnel effect, is higher for smaller angles of incidence.

In the Fresnel term it is impossible to separate the geometry and wavelength parameters. But this separation is a core idea of the general dichromatic reflection model. Thus, in order to incorporate the more physically-accurate Fresnel term, one has to augment Eq. 2 as follows:

$$\begin{aligned} I(\mathbf{x},\lambda) &= w_d(\mathbf{x})S_d(\mathbf{x},\lambda)E(\lambda) \\ &+ w_s(\mathbf{x})F(\theta_i,\lambda)E(\lambda), \end{aligned} \tag{7}$$

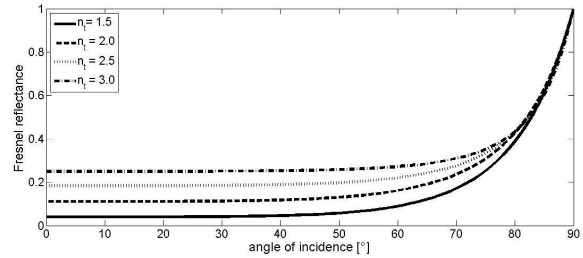

Fig. 1. Fresnel reflectances for variable n_t and $n_i = 1.0$.

	Skin (epidermis)		Mineral oil	
	λ	$n(\lambda)$	λ	$n(\lambda)$
R	633	1.433	643	1.46744
G	532	1.448	546	1.47149
B	442	1.449	467	1.47685

Table 1. Refractive indices of skin and mineral oil [12, 13]. The indices of air are set to $n(R) = n(G) = n(B) = 1.000293$ [11].

with a geometrical factor

$$w_s(\mathbf{x}) = \frac{D(\mathbf{x})G(\mathbf{x})}{\pi(N\cdot L)(N\cdot V)}. \tag{8}$$

As specularity-based illuminant color estimation algorithms are based on the dichromatic reflection model and the neutral interface reflection assumption, the result of these approaches is not the pure illumination color $E(\lambda)$ but the combination of the illumination color multiplied with the Fresnel term $F(\lambda,\theta_i)$. As the computed estimate does not only consider regions of the same θ_i, the introduced error is a mixture of the surface reflection ratio at different angles of incidence.

4. CONSIDERATIONS OF SPECULAR SKIN REFLECTANCE

In order to get an indication of the inaccuracy introduced by the NIR assumption, we analyzed the Fresnel effect for refractive indices of human skin in the RGB color space. As reference indices we used n_t values of the human epidermis itself [12] and of mineral oil [13], which exhibits similar reflectance behavior as oily skin. The analyzed refractive indices are listed in Tab. 1. Air was taken as the incident medium [11].

Because the values of the refractive index are small, we calculated the percent change in the index of refraction in measurements taken at consecutive wavelengths. The total variation Δn, is given by the sum of the absolute values of the percent changes between the consecutive wavelengths [10],

$$\Delta n = 100\left(\frac{|n(G)-n(B)|}{n(B)} + \frac{|n(R)-n(G)|}{n(G)}\right), \tag{9}$$

where the refractive indices $n(c)$, with $c \in \{R,G,B\}$ are chosen as in Tab. 1. The total variation in the Fresnel coefficients, $\Delta F(\theta_i)$, is similarly computed.

Tab. 2 lists the total variations for epidermis and mineral oil. It is noticeable, that even small variations in the refractive index can result in an amplified effect on the surface reflection ratio. Fig. 2 illustrates the wavelength-dependency of the Fresnel term. For the

Material	Δn	$\Delta F(\theta_i = 0°)$	$\epsilon(\theta_i = 0°)$
Skin (epidermis)	1.10%	5.80%	1.54°
Mineral oil	0.64%	1.20%	0.76°

Table 2. Changes in the value of the refractive index Δn, the resulting changes in the Fresnel term $\Delta F(\theta_i = 0°)$ and the angular error $\epsilon(\theta_i = 0°)$ of illuminant estimation techniques based on the neutral interface reflection assumption.

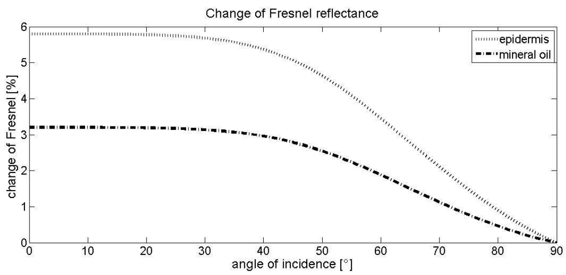

Fig. 2. Total variation of the Fresnel reflectance of the epidermis and mineral oil.

epidermis, the highest change occurs at $\theta_i \in [0°, 35°]$ with a value of approximately 5.8% and drops for larger angles of incidence. The curve for mineral oil exhibits similar tendencies.

Therefore, especially for the illuminant estimation techniques based on specularities, the following question arises: How much error does the neutral interface reflection assumption introduce to the illuminant estimation outcomes? The error metric used in the evaluation of many color constancy algorithms based on benchmark datasets is the angular error,

$$\epsilon = \cos^{-1}\left(\frac{\mathbf{E}_t \cdot \mathbf{E}_e}{\|\mathbf{E}_t\|\|\mathbf{E}_e\|}\right), \tag{10}$$

where $\mathbf{E}_t$ and $\mathbf{E}_e$ are the true and estimated illumination color vectors. We computed the error between a reference illuminant $\mathbf{E}_t = (E(\lambda = R), E(\lambda = G), E(\lambda = B))^T = (1, 1, 1)^T$ and the illuminant estimated under NIR. Recall that under NIR the estimated illuminant is the combined $E(\lambda)$ and $F(\theta_i, \lambda)$ term, i.e. the estimated color is $\mathbf{E}_e(\theta_i) = (F(\theta_i, \lambda = R)E(\lambda = R), F(\theta_i, \lambda = G)E(\lambda = G), F(\theta_i, \lambda = B)E(\lambda = B))^T$. As the combined term depends on the angle of incidence, the error measure, $\epsilon(\theta_i)$, also shows this dependency. Computed for the epidermis and mineral oil, the introduced errors are shown in Fig. 3 and listed in Tab. 2. In recent evaluations (e.g. [14, 15]), the reported angular errors of state-of-the-art illuminant estimation techniques range from $\epsilon = 3.6°$ to more than $20.0°$. Compared to these values, the error introduced by the neutral interface reflection is up to 20% for mineral oil and even up to 40% for the epidermis.

5. MATERIAL-DEPENDENT ILLUMINATION COLOR ESTIMATION

The considerable error introduced by the NIR could be corrected if the images regions used in illuminant color estimation are of materials with known refractive indices. As in the theoretical considerations we show our proposed correction on skin. Our approach is not a stand-alone estimation technique, but a correction scheme, which can be combined with existing specularity-based methods,

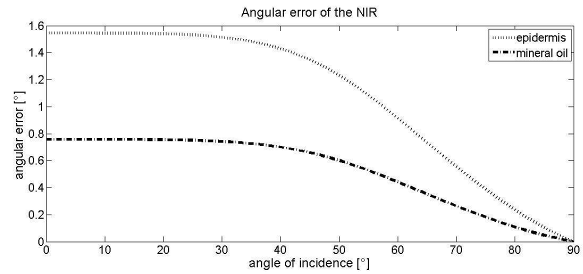

Fig. 3. Angular error introduced by the NIR assumption during a specularity-based illumination estimation on skin (epidermis) and mineral oil.

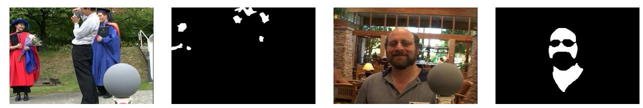

Fig. 4. Examples for evaluated images and segmented skin masks.

like [6, 7, 8, 9, 16]. To our knowledge, no such material-dependent correction has been presented yet in the literature.

As the estimated illuminant $E_e(\lambda)$ is the product of the true illuminant $E(\lambda)$ and the Fresnel term $F(\theta_i, \lambda)$, the correction can be achieved with

$$\begin{aligned} E_e(\lambda) = F(\theta_i, \lambda)E(\lambda) \quad &\Rightarrow E(\lambda) = E_e(\lambda)/F(\theta_i, \lambda) \\ &\Rightarrow E(\lambda) \approx E_e(\lambda)/\bar{F}(\lambda). \end{aligned} \tag{11}$$

The problem is, that typically θ_i is unknown for individual pixels. Therefore, the correction is done by scaling with an average factor $\bar{F}(\lambda)$. The evaluation of an adequate average correction factor is shown in section 5.2.

5.1. Methods and Data

The proposed method was evaluated on the basis of the color constancy database published by Ciurea and Funt [17], which provides ground truth illuminant colors. We took a subset of 24 indoor and 7 outdoor images, containing larger regions of human skin. The skin segmentation was performed manually. Two examples are give in Fig. 4. As illuminant estimation technique the voting scheme by Riess *et al.*[16] was chosen.

5.2. Results

For the evaluation we computed the illuminant estimation on skin regions only. Afterwards, we compared the angular errors without and with the proposed correction scheme. As scaling factors we tried different factors $\bar{F}(\lambda)$ by testing various values of θ_i, i.e. $\bar{F}(\lambda) = F(\theta_i, \lambda)$ for $\theta_i \in [0°, 90°]$.

The result of the proposed method is shown in Fig. 5, where the achieved errors are averaged over all tested images. Two major aspects can be observed: Firstly, the correction with the Fresnel reflectance of both, the epidermis and mineral oil, resulted in an improved illuminant estimation. However, the enhancement with epidermis values is much higher than with oil. Secondly, for both materials, the best results where accomplished with $\theta_i = 0°$, which corresponds to the highest possible color shift. For these correction factors, the angular error could be reduced from $5.24°$ to $4.84°$ (mineral oil) and $4.09°$ (epidermis). As we noted previously, the total variation of the Fresnel term is almost constant for a wide range (see

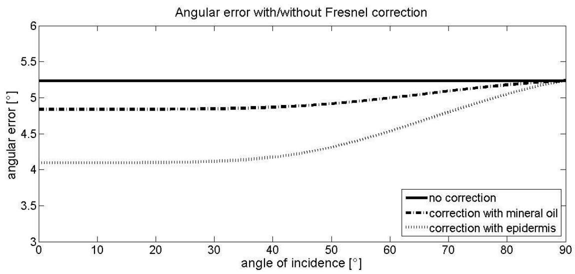

Fig. 5. Angular errors without and with the proposed Fresnel correction. The curves are obtained with different angles of incidence.

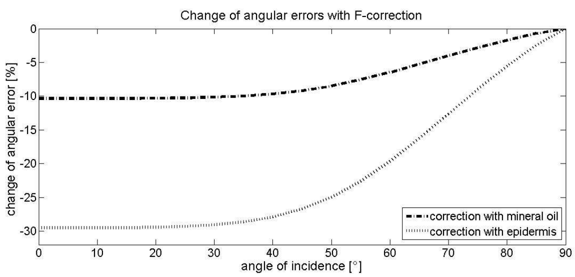

Fig. 6. Percent change of the angular error after Fresnel correction.

Fig. 2) of angles of incidence. Therefore, it seems, that the Fresnel correction is robust against wrongly selected incident angles. However, in the future further analyses have to be done to relate image content and Fresnel correction properly. In Fig. 6 the average percent change of the angular error due to the Fresnel correction is shown. The scaling with mineral oil Fresnel reflectances results in an reduction of the angular error of 10.13%, the epidermis values even decrease the error by 29.5%.

6. CONCLUSIONS

In this paper we have analyzed the influence of the neutral interface reflection assumption on specularity-based illuminant color estimation techniques. Our theoretical analysis showed that the originally omitted color shift of the Fresnel reflectance can result in a significant angular error. Furthermore, we proposed a material-dependent correction method, which resulted in a considerable improvement of the estimated illuminant color (29.5% for epidermis and 10.13% for mineral oil). All results were shown for human skin in combination with the refractive indices of the epidermis and mineral oil.

The presented evaluations are preliminary results. For a better understanding of the Fresnel effect on physics-based estimation techniques and for an improved material-dependent correction scheme, further evaluations are required. Among other things, this includes the influence of gamma, image compression, robustness regarding inaccurate material segmentation and transferability to other materials.

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8. REFERENCES

[1] R. L. Cook and K. E. Torrance, "A Reflectance Model for Computer Graphics," *ACM Transactions on Graphics*, vol. 1, no. 1, pp. 7–24, 1982.

[2] S. A. Shafer, "Using Color to Separate Reflection Components," *Color Research and Application*, vol. 10, no. 4, pp. 210–218, 1985.

[3] H.-C. Lee, E. J. Breneman, and C. P. Schulte, "Modeling Light Reflection for Computer Color Vision," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 12, no. 4, pp. 402–409, 1990.

[4] S. Lin and H.-Y. Shum, "Separation of Diffuse and Specular Reflection in Color Images," in *IEEE Conference on Computer Vision and Pattern Recognition*, Kauai, Hawaii, 2001, vol. 1, pp. 341–346.

[5] R. Tan and K. Ikeuchi, "Separating Reflection of Textured Surfaces using a Single Image," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 27, no. 2, pp. 178–193, 2005.

[6] H.-C. Lee, "Method for Computing the Scene-Illuminant Chromaticity from Specular Highlights," *Journal of the Optical Society of America A*, vol. 3, no. 10, pp. 1694–1699, 1986.

[7] G. J. Klinker, S. A. Shafer, and T. Kanade, "The Measurement of Highlights in Color Images," *International Journal of Computer Vision*, vol. 2, no. 1, pp. 7–26, 1992.

[8] R. Tan, K. Nishino, and K. Ikeuchi, "Color Constancy through Inverse-Intensity Chromaticity Space," *Journal of the Optical Society of America A*, vol. 21, no. 3, pp. 321–334, 2004.

[9] J. Toro, "Dichromatic Illumination Estimation Without Pre-Segmentation," *Pattern Recognition Letters*, vol. 29, no. 7, pp. 871–877, 2008.

[10] E. Angelopoulou, "Specular Highlight Detection Based on the Fresnel Reflection Coefficient," in *IEEE International Conference on Computer Vision*, Rio de Janeiro, Brazil, 2007.

[11] E. Hecht, *Optics, 4th ed.*, Addison Wesley, 2001.

[12] H. Ding, J. Q. Lu, W. A. Wooden, P. J. Kragel, and X. H. Hu, "Refractive Indices of Human Skin Tissues at Eight Wavelengths and Estimated Dispersion Relations Between 300 and 1600 nm," *Physics in Medicine and Biology*, vol. 51, no. 6, pp. 1479–1489, 2006.

[13] J. R. Verkouteren and S. D. Leigh, "New Low-Index Liquid Refractive Index Standard SRM 1922," *Fresenius' Journal of Analytical Chemistry*, vol. 367, no. 3, pp. 226–231, 2000.

[14] K. Barnard, L. Martin, A. Coath, and B. Funt, "A Comparison of Computational Color Constancy Algorithms – Part II: Experiments With Image Data," *IEEE Transactions on Image Processing*, vol. 11, no. 9, pp. 985–996, 2002.

[15] R. Lu, A. Gisjenij, T. Gevers, V. Nedovic, D. Xu, and J.-M. Geusebroek, "Color Constancy using 3D Scene Geometry," in *IEEE International Conference on Computer Vision*, Kyoto, Japan, 2009.

[16] C. Riess, E. Eibenberger, and E. Angelopoulou, "Illuminant Estimation by Voting," Tech. Rep., Friedrich-Alexander Universität Erlangen-Nürnberg, 2009.

[17] F. Ciurea and B. Funt, "A Large Image Database for Color Constancy Research," in *Color Imaging Conference*, Scottsdale, Arizona, USA, 2003, pp. 160–164.