Color Consistency of Specular Highlights in Consumer Cameras

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ABSTRACT

The latest advancements in Augmented Reality (AR) and Diminished Reality (DR) have allowed the development of many consumer-oriented applications (such as sales and driving aid, or education). To increase the realism in rendering, estimating the illumination in the scene is a key element. A lot of works tackle this problem but rarely discuss the color of the reconstructed illumination. The Dichromatic Model indicates that the specular component is not affected in color by the texture underneath and holds the light source's color. Though theoretically sound, in practice consumer cameras are subject to nonlinear behaviors which change RGB ratios and create inconsistencies when estimating the illumination. In this paper, we study the conditioning and limits of inverting local illumination models while relying on the Dichromatic Model. We show that the reconstructed specular component has an inconsistent color because it changes depending on the surface's colors.

CCS CONCEPTS

• **Computing methodologies → Computer vision**; *Mixed / augmented reality*; *Camera calibration*;

KEYWORDS

Dichromatic model, local illumination, reflectance, color consistency, specular highlight, saturation, Augmented Reality.

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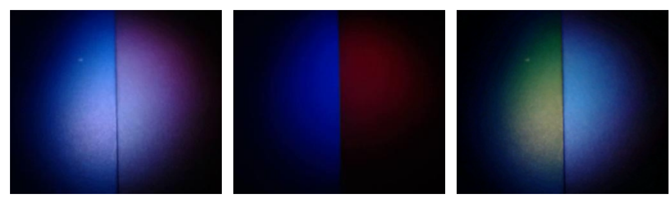
1 INTRODUCTION

Augmented Reality relies more and more on SLAM methods which have recently matured in terms of computational speed and geometry accuracy, opening new possibilities. Many studies attempted to estimate the lighting conditions of a scene automatically (according to a local illumination model such as Phong, Blinn-Phong), in order to extend even more the scope of the possible applications. This is a difficult and ill-posed problem due to the correlation between the remaining unknown parameters: the light source's position, its color, the surface's roughness and its specular and diffuse parts of reflectance. In this context, the rendering quality is of utmost importance for good immersion of the user and this relies on the capacity to estimate the illumination model accurately. To that extent, these light's parameters should match in terms of position and visual aspect seamlessly with the input video stream, which includes the specular component's color. This latter aspect is not really discussed in the literature.

According to the Dichromatic Reflection Model of Shafer [1985], the color of specularities is the same as the illumination which means that the surface color does not influence the specularity color. Most works that do not use gray scale assume it to be true. In practice though, we observe otherwise as seen in figure 1. In fact, consumer cameras do not have a linear response, as assumed by the Dichromatic Model, which undermines its validity. Different colors are affected differently, inducing color shifts and creating inconsistencies regarding the color of specular highlights.



(a) Source image (b) Diffuse (c) Specular

Figure 1: This figure shows in (a) a specularity on both a blue and a red planar object. (b) The diffuse component is extracted with polarizers. (c) Specular component is obtained by a subtraction operation (a) - (b). We observe in (c) an inconsistency of the specular component's color, which should have the same color on both surfaces (according to the dichromatic model).

Contribution. This work aims to identify the causes of the color inconsistency problem and its consequences on the illumination estimation technique. We then present two specific situations that can induce color inconsistency.

2 RELATED WORK

Most existing works separate the specular from the diffuse component in order to estimate the illumination model [Hara et al. 2005; Xu and Wallace 2008]. They often evaluate the geometric accuracy of their estimation (light source's position and surface roughness, which represents the expansion of the specularity) but do not discuss the specular color inconsistency problem, which clearly exists for consumer cameras as shown in figure 1. Works tend to use the Dichromatic Model for the estimation but the model has its limits. Since no insight can be found as how to avoid this problem, we felt it necessary to address this problem and maybe raise awareness.

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3 LIMITS OF THE DICHROMATIC MODEL

3.1 Dichromatic Model (DM)

When light rays hit an opaque surface, two kinds of reflections occur: the diffuse or body reflection, which is the light that penetrates the object and scatters, allowing us to see the object's color, and the specular or interface reflection, which is a mirror-like reflection of the light source, dependent on the viewer position. Shafer [Shafer 1985] estimated that the specular reflection holds approximately the illumination's color. The Dichromatic Model states then that the intensity on a surface is the linear combination of these two reflections, which writes at a specific point and after a tristimulus integration (*e.g.* standard RGB camera):

$$\begin{bmatrix} R & G & B \end{bmatrix}^\top = m_s \mathbf{C_s} + m_d \mathbf{C_d}, \tag{1}$$

where m_s and m_d are respectively the specular and diffuse geometric coefficients, and $\mathbf{C_s}$ and $\mathbf{C_d}$ are the specular and diffuse colors (after RGB integration).

According to the model, we can therefore separate the specular component by subtracting the diffuse component $m_d\mathbf{C_d}$, which is a method used in most previous works [Hara et al. 2005; Xu and Wallace 2008] to estimate the illumination model. Moreover, the estimated color $\mathbf{C_s}$ should be the same no matter the surface color.

3.2 DM and Linearity of the Inter-Color Variations

In this section we demonstrate that the DM implies a linearity of the inter-color variations. Indeed, the DM holds because Shafer [Shafer 1985] does not consider the built-in processing of the camera and considers a perfect linear tristimulus integration:

$$\mathbf{C}_\mathbf{X}^{raw}(i) = \int_\lambda X(\lambda)\rho_i(\lambda)\mathrm{d}\lambda, \tag{2}$$

where $\mathbf{C}_\mathbf{X}^{raw} = \begin{bmatrix} R & G & B \end{bmatrix}^\top$ is the raw pixel value, $X(\lambda)$ is the Spectral Power Distribution (SPD) recorded by the camera, $i = \{1, 2, 3\}$ stands for the channel $\{R, G, B\}$ and $\rho(\lambda) = \{\bar{r}(\lambda), \bar{g}(\lambda), \bar{b}(\lambda)\}$ is the channels' responsivity. Actually, a camera's response is rarely linear unless it is radiometrically calibrated. This nonlinearity can create color shifts, changes in the relative RGB values. This is inconvenient for estimating a consistent color of the illumination because the separation of the specular component becomes inconsistent:

$$\mathbf{C_{m_s X_s + m_d X_d}} \neq \mathbf{C_{m_s X_s}} + \mathbf{C_{m_d X_d}} \tag{3}$$

$$\mathbf{C_{m_s X_s + m_d X_d}} - \mathbf{C_{m_d X_d}} \neq \mathbf{C_{m_s X_s}} \tag{4}$$

where $\mathbf{C_X}$ is the real pixel value of a SPD X, and X_s and X_d are the SPDs of the specular and diffuse reflections. Without linearity, equation (3) directly contradicts equation (1). The consequences can be observed in the figure 1 where the attempt to separate the specular components on two surfaces results in two different colors.

3.3 Cases Implying Non-Linearity of the Inter-Color Variations

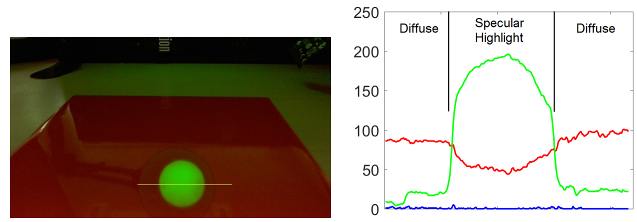
In this section, we show that there are at least two kinds of phenomena that induce nonlinearity, one related to the device and the recording (sensor, optics) and another to the pre-processing before the image is displayed. In the same order, we will present one example of each kind.

Channel Saturation due to Exposure

The user should pay attention to the camera exposure since pixels associated to specular reflections tend to be the firsts to be saturated in the image. This changes the RGB ratio if one or two channels are saturated before the other(s), inducing nonlinearity due to the shape of the camera response function [Debevec and Malik 1997].

Adjusting Color Saturation

Adjusting color saturation is a processing that converts the pixel values from the RGB color space to another (HSV, HSL) and then converts it back. It is clear from the relations between RGB and S that this induces nonlinearity, which we can see in figure 2.



(a) Source image and the profile line **(b) RGB profile along the yellow line**

Figure 2: Image taken with excessive color saturation

Figure 2 is a real image of an orange surface on which we observe the specular reflection of a green light[1]. The imaging device is a standard webcam. The RGB profile clearly shows that the additive aspect of the dichromatic model does not hold: the specular highlight should be a linear combination of two colors but the red component decreases because the saturation is set by the user to make the green more vivid. This color shift can in worst cases make the specular component's and therefore the light source's color reconstruction inconsistent, as in figure 1.

4 CONCLUSION & DISCUSSION

We highlight an issue in color consistency when inverting an illumination model using consumer cameras. Although most of the real-world light sources have a white color, more and more colored light sources are found in practice thanks to the technology of Light-Emitting Diodes (LED). It is therefore necessary to address this problem. AR and DR does not aim to retrieve the real color but rather a consistent color of the light source throughout the video stream. Otherwise, the light source's color would be inconsistent for a different surface color from the one used for the estimation. For future works, it will be interesting to study in more details the impact of this color inconsistency in AR and DR applications.

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[1] SAMSUNG LED BLUETOOTH GB9000 X3 SMART BULB