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Pattern Recognition 41 (2008) 2461–2469
PATTERN RECOGNITION
THE JOURNAL OF THE PATTERN RECOGNITION SOCIETY
www.elsevier.com/locate/pr

Chromaticity-based separation of reflection components in a single image

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Received 30 May 2007; received in revised form 24 January 2008; accepted 28 January 2008

Abstract

The separation of diffuse and specular reflection components, or equivalently specularity removal, is required in the fields of computer vision, object recognition and image synthesis. This paper proposes a simple and effective method to separate reflections in a color image based on the error analysis of chromaticity and appropriate selection of body color for each pixel. By solving the least-squares problem of the dichromatic reflection model, reflection separation is implemented on a single pixel level, without requiring image segmentation and even local interactions between neighboring pixels. Experimental evaluation indicates that the proposed method is effective and can deal with a wide variety of images.

Keywords: Reflection components separation; Diffuse reflection; Specular reflection; Chromaticity; Dichromatic reflection model; Image restoration

1. Introduction

For a wide variety of inhomogeneous materials, including plastic, wood, ceramic and other opaque nonconductors with uniform pigmentation, the reflection is the combination of diffuse reflection and specular reflection, which can be well described by the dichromatic reflection model introduced by Shafer [1]. The role of specular reflection is very important in the fields including computer vision [2,3], object recognition [4,5] and image content editing [6,7]. As many algorithms in computer vision and object recognition assume that the scene contains only diffuse reflection, they will become erroneous in the existence of specular reflection. As the specular reflection is relevant to the roughness of object surface, it should be first recovered and then incorporated in the simulation of new object appearances. With these regards, it is often desired to separate the diffuse and specular reflection components accurately from one or more images [8–12].

1.1. Previous work

Many methods for separating reflection components have been proposed in the literature. Nayar et al. [8] used a polarization filter to identify the highlights based on the fact that, for dielectric materials, the specular component is polarized while the diffuse component is not. The work of Tan et al. [9] was the first one that proposed the concept of specular-free (SF) image, which contains the identical geometry of the original image while eliminates the specular reflection components. Through the intensity logarithmic differentiation on both of the original and SF images, the pixels containing only diffuse reflections can be successfully localized. The specular components of highlight pixels are then removed in a two-pixel neighborhood region by employing an iterative framework. Tan et al. [10] also proposed another method for separating reflection components of uniformly colored surfaces based on the analysis of chromaticity and noise in the maximum chromaticity–intensity space.

Park and Lee [11] proposed a highlight inpainting method based on color line projection, by employing two images captured under different exposure times. Mallick et al. [12] proposed a unified framework to separate two reflection components from images and videos by using a partial differential equation approach. Their work also showed that different object surface appearances could be simulated by editing and recombining these two reflection components. Tan et al. [13] introduced an image inpainting technique for highlight removal without losing surface textures, by using the partially available information of diffuse reflections in the highlight areas.

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doi:10.1016/j.patcog.2008.01.026

1.2. Contributions of our method

It is noted that most of the previous works deal with the separation of reflection components by color projection or color shift in RGB space or a specified color space [9,11,13]. When the objects are not uniformly colored, preprocessing procedures such as image segmentation are needed before applying the method proposed in Ref. [10]. When there are multicolored objects or textures in the scenes, the local interactions between pixels must be considered in many methods [9,12,13], which makes the algorithm complicated to implement. Although the method introduced by Nayar et al. [8] can obtain accurate results, using an additional polarization filter seems impractical in many imaging circumstances.

In this study, we propose a simple and effective method to separate the diffuse and specular reflection components by the direct use of dichromatic reflection model [1]. It is known that the diffuse reflection represents the intrinsic properties of the object surfaces, while the color of the specular reflection is always the same to that of the illuminant [14]. Hereafter, the RGB vector (camera response) of the intrinsic material spectral reflectance is referred as body color, and the RGB vector of the spectral power distribution of the imaging illuminant is termed as illuminant color. The illuminant color can be simply acquired by imaging a white object surface. If this is not applicable, the illuminant color can be estimated using color constancy algorithms [15]. It is obvious that if the body color is known, the proportions of the diffuse and specular reflection components can be easily computed by solving the dichromatic equation under the least-squares criterion [6]. As image segmentation and other image operations are usually inappropriate to complex scenes, the proposed method estimates the body color for each pixel based on chromaticity analysis.

In the proposed method, a new SF image and a modified SF (MSF) image are introduced. The SF image is obtained by subtracting the minimum RGB value at each pixel position, and the MSF image is formed by adding a same scalar value for each pixel on the SF image. The noise analysis indicates that the MSF image is more robust than the SF image, and therefore the former is used to compute the chromaticity for each pixel. The approximate diffuse and specular candidates are decided according to the difference between the MSF and original images. Then, by iterative selection of body colors and calculation of chromaticity differences, the diffuse and specular reflection components are appropriately separated by the least-squares technique.

The rest of this paper is organized as follows. Section 2 presents the concept of the SF and MSF images, and their robustness of chromaticity with respect to imaging noise is analyzed statistically. Section 3 outlines the procedure for separating diffuse and specular reflections in a color image. Experimental results and discussion are provided in Section 4. Section 5 is the conclusion of this paper.

2. Specular-free images and chromaticity analysis

According to the dichromatic reflection model, the color $\mathbf{V}(p)$ of a pixel p is the linear combination of diffuse reflection component with body color $\mathbf{V}_\mathrm{b}$ and specular reflection component with surface color $\mathbf{V}_\mathrm{s}$:

$$\mathbf{V}(p) = \alpha(p)\mathbf{V}_\mathrm{b} + \beta(p)\mathbf{V}_\mathrm{s} \tag{1}$$

where $\alpha(p)$ and $\beta(p)$ are the coefficients (or proportions) of the diffuse and specular reflection components, respectively. The illuminant color can be obtained by imaging a white object surface or estimated using color constancy algorithms. Then the color of each pixel is first normalized with respect to the illuminant color and then rescaled to the range 0–255 [10]. By this operation the surface color becomes pure white, or more precisely, $\mathbf{V}_\mathrm{s}=[255, 255, 255]^\mathrm{T}$, with the superscript T denoting vector transpose. It is obvious from Eq. (1) that, as the colors contain three components, i.e., red, green and blue, the two coefficients $\alpha(p)$ and $\beta(p)$ can be computed using least-squares, provided that the body color $\mathbf{V}_\mathrm{b}$ is available. The following subsections illustrate how the body color $\mathbf{V}_\mathrm{b}$ of each pixel can be decided by the chromaticity analysis of the MSF image.

2.1. SF and MSF images

The concept of SF image was first introduced by Tan et al. [9]. In their work, the SF image is obtained by setting the diffuse maximum chromaticity equal to a scalar value for all pixels, and computing the estimated specular components from the original colors. The geometry information of their SF image is the same to that of the original image, but the color information may be quite different [9]. Fig. 1(d) shows the SF image of a fish image using their method when the diffuse maximum chromaticity is set to 0.5.

As the most important purpose of SF image is to eliminate the specular reflection components, it can actually be produced in a very simple manner, i.e., by subtracting the minimum of the RGB components of the color $\mathbf{V}(p)$:

$$\begin{aligned} V_{\mathrm{sf},i}(p) &= V_i(p) - \min(V_1(p), V_2(p), V_3(p)) \\ &= V_i(p) - V_{\min}(p) \end{aligned} \tag{2}$$

where $V_i(p)$ is the ith element of color $\mathbf{V}(p)$, and $V_{\mathrm{sf},i}(p)$ is the ith element of the SF color $\mathbf{V}_\mathrm{sf}(p)$, and

$$\begin{aligned} V_{\min}(p) &= \min(V_1(p), V_2(p), V_3(p)) \\ &= \alpha(p)\min(V_{\mathrm{b},1}, V_{\mathrm{b},2}, V_{\mathrm{b},3}) + \beta(p)V_\mathrm{s} \\ &= \alpha(p)V_{\mathrm{b},\min} + \beta(p)V_\mathrm{s} \end{aligned} \tag{3}$$

where $V_{\mathrm{b},i}$ is the ith element of body color $\mathbf{V}_\mathrm{b}$, $V_{\mathrm{b},\min} = \min_i(V_{\mathrm{b},i})$ and V_s is the component of color $\mathbf{V}_\mathrm{s}$. Note that the subscript i of V_s is omitted as the surface color $\mathbf{V}_\mathrm{s}$ is pure white after the normalization with respect to illuminant color. By combining Eqs. (2) and (3), the SF color can be rewritten as

$$V_{\mathrm{sf},i}(p) = \alpha(p)(V_{\mathrm{b},i} - V_{\mathrm{b},\min}) \tag{4}$$

It is clear from Eq. (4) that the specular component is eliminated while the geometry information is reserved in the SF image.

It can be observed from Eq. (4) that, as $V_{\mathrm{b},\min} = \min_i(V_{\mathrm{b},i})$, at least one element of the vector $\mathbf{V}_\mathrm{sf}(p)$ is 0, and hence the color appearance of the SF image is always darker than that of the original image.