Obtaining the Diffuse Reflection from a Single Color Image

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Abstract

From an RGB color image and under the assumption that the color of the illuminating light is known, a method for recovering the diffuse reflection component of the observed scene is proposed. In contrast to previously proposed approaches, no direct spatial connection of pixels properties is assumed. Drawing upon the dichromatic reflection model, the specular-free image is produced by projecting each observed color onto a plane that is tangent to an estimate of the material's body reflection color. Body color estimates are obtained by looking at how observed colors distribute in RGB space. The proposed approach is tested on synthetic and real images.

Introduction

Commonly, an image results from the blending of different reflection properties. In computer vision, the study of each reflection property individually is often desired. In this paper, an approach to disentangle the body from the interface reflection of observed surfaces is proposed. Contrary to previously proposed approaches, the proposed technique makes no strong spatial connectivity assumption of pixels properties.

Several approaches for recovering a specular-free image from a single RGB image have been proposed. Klinker *et al.* [3] put forward an approach that efficaciously cope with uniformly colored dielectric surfaces under singly colored scene illumination. Bajcsy *et al.* [1] used region-growing segmentation techniques based on hue and saturation to identify material coherent regions as a preliminary step to producing the specular-free image. These approaches rely on a strong spatial connection of pixels properties, which may be an unfavorable requirement when highly cluttered scenes are considered. Looking at relaxing the spatial connectivity assumption of previously proposed techniques, Tan and Ikeuchi [8] proposed an iterative approach based on the chromaticity difference of two neighboring pixels. Although large uniform regions are no longer required, the relationship between two neighboring pixels is still needed.

The approach of this paper relies upon the observation made by Shafer [7] that the colors displayed by the same material, independent of how they may be spatially distributed, lie on a plane in RGB space in between the color of the body reflection and a color related to the color of the illuminating light. Previously proposed approaches also rely on this same observation, but the method of this paper differs from them in two aspects: (i) in how the specular-free image is recovered, and (ii) in how the color of the body reflection of each material, in an image region possibly encompassing several different materials, is discovered. The specular-free image is recovered by projecting each observed color onto a plane that is tangent to an estimate of the body color. Body colors are estimated by looking at the distribution of observed colors in RGB space.

The Dichromatic Reflection Model and the Problem

The *dichromatic reflection model* [7] states that the color reflected by an inhomogeneous dielectric material can be written as the linear combination of two independent colors: the color of the body (diffuse) reflection, which depends on the reflection properties of the material; and the color of the interface (specular) reflection, which under the assumption of *neutral interface reflection* [4] is essentially the color of the illuminating light. If the spectral properties of the illuminant are constant throughout the scene, the imaged colors at each pixel location $\mathbf{x} \in \mathbb{R}^2$ can be written as

$$\mathbf{c}(\mathbf{x}) = m_b(\mathbf{x})\mathbf{b}(\mathbf{x}) + m_s(\mathbf{x})\mathbf{s}, \tag{1}$$

where $\mathbf{s}$ is the color of the interface reflection (the color of the illuminating light), $\mathbf{b}(\mathbf{x})$ is a piecewise constant vector function indicating the body color of the different surfaces (materials) in the scene, and $m_b(\mathbf{x})$ and $m_s(\mathbf{x})$ are non-negative scalar functions expressing the dependency of the reflected light on geometry.

Given an RGB color image $\mathbf{c}(\mathbf{x})$, expressible in the form of Equation (1), and assuming that the chromaticity of the illuminating light (vector $\mathbf{s}$) is known, the problem set out here is that of retrieving the specular-free image $m_b(\mathbf{x})\mathbf{b}(\mathbf{x})$.

Removing Specularities

The specular-free image is recovered by projecting each observed color onto a plane in RGB space.

Projection schemes have been previously proposed [9, 5], but they have been aimed at producing an image with intensity values bearing a direct relationship with the diffuse geometrical component of the reflected light (function $m_b(\mathbf{x})$), regardless of what the actual color of the diffuse reflection may be. In [9] and [5] it has been shown that by projecting the observed colors by parallel rays having the same direction as the color of the illuminating light, the diffuse geometrical component of observed surfaces can be recovered up to a proportional multiplicative factor. In [9], colors are projected onto a cone with vertex in the origin of the RGB space and axis direction given by the color of the illuminating light. In [5], the projection is carried out onto the plane that goes through the origin and that is perpendicular to the light. In contrast to [9] and [5], in this paper, the projection is carried out onto a slanted plane (a plane that is not orthogonal to the color of the light). This is simpler than projecting onto a cone, which requires solving a second-degree polynomial, and offers, by contrast with [5], a direct mechanism to producing images with valid RGB coordinates.

Suppose that the actual color of the body reflection, vector $\mathbf{b}$, is known. The diffuse component, vector $\mathbf{d}$ $(= m_b\mathbf{b})$, of an observed color $\mathbf{c}$ can then be obtained by multiplying $\mathbf{c}$ by the

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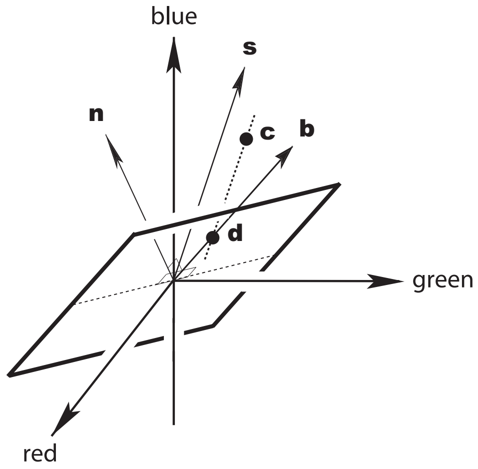

Figure 1. Removing specularities. Assuming that the color of the illuminating light (vector $\mathbf{s}$*) and the actual body color (vector* $\mathbf{b}$*) of the reflected light are known, the body component (vector* $\mathbf{d}$*) is obtained by projecting the observed color (vector* $\mathbf{c}$*) onto the plane defined by vector* $\mathbf{n}$ *following the same direction as vector* $\mathbf{s}$*. Note that color values are referred to as points and as vectors in RGB space.*

projection matrix defined as

$$P = I - \frac{\mathbf{s}\mathbf{n}^T}{\mathbf{s}^T\mathbf{n}}, \tag{2}$$

where I is the identity matrix and $\mathbf{n}$ is a vector perpendicular to the body color $\mathbf{b}$ and lying on the plane defined by $\mathbf{s}$ and $\mathbf{b}$, which can be computed as

$$\mathbf{n} = (\mathbf{b}^T\mathbf{b})\,\mathbf{s} - (\mathbf{b}^T\mathbf{s})\,\mathbf{b}. \tag{3}$$

The projection matrix P is a compact form of expressing, upon multiplication with $\mathbf{c}$, the intersection between the line passing through $\mathbf{c}$ with direction $\mathbf{s}$ and the plane with normal vector $\mathbf{n}$ (Figure 1). Note that the body component can also be obtained by directly projecting onto the normalized vector of $\mathbf{b}$, as proposed by Klinker *et al.* [3]. This forces the chromaticity of all projected colors to have the same chromaticity of $\mathbf{b}$. In this paper, however, the projection onto the slanted plane is preferred because $\mathbf{b}$ itself is not, in general, explicitly known.

Observe that any color having the same chromaticity as that of $\mathbf{b}$ (that is, a color that can be written as $k\mathbf{b}$, for some constant k) produces the same projection matrix P. Indeed, any color written as $k\mathbf{b}$ induces only a variation in the amplitude of $\mathbf{n}$ that is then cancelled out when taking the ratio of $\mathbf{s}\mathbf{n}^T$ and $\mathbf{s}^T\mathbf{n}$ in Equation (2). As such, to recover the body component, only the chromaticity of the body reflection is required.

Finding Body Colors

Body colors are found by analyzing in RGB space the distribution of observed colors.

It can be seen from the previous section that the problem of producing a faithful specular-free color image has largely to do with reliably resolving the body color of observed materials. This task has been dealt with by others by considering the color of pixels within image regions. In principle, if in a region there are colors that are purely diffuse, it is then possible to estimate the chromaticity of the diffuse reflection by identifying those purely diffuse colors. In the approach proposed here, the body colors are also resolved by exploring the colors within regions. For any given region, which may embody colors emanating from several different materials, body colors are sought sequentially. Colors that may have emanated from the same material are first identified. From these colors, a candidate for the chromaticity of the diffuse reflection is then estimated.

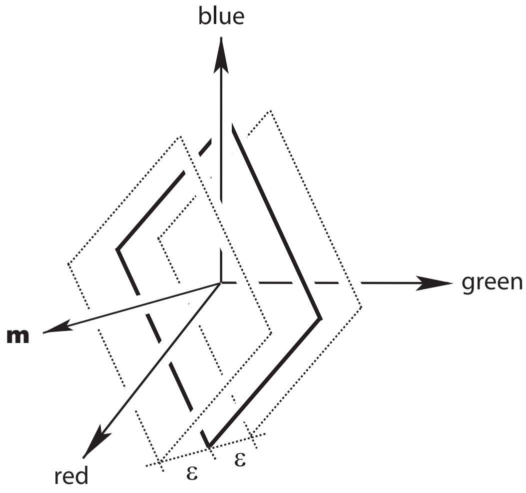

Figure 2. Finding Body Colors. The gap between two parallel planes equally distant from the origin (dashed lines in the diagram) is used to inspect the color space. Observed colors falling within the gap are considered to be produced by the same material. The orientation of the gap is defined by vector $\mathbf{m}$*; its width, by* ε*. The plane passing through the origin (bold lines) is the dichromatic plane of the material. Observed colors within the gap are used to estimate the body color of the material.*

Colors emanating from the same material are identified by using the constraint stated by the dichromatic reflection model, i.e., that all colors from the same material must lie on a plane in RGB space that contains the color of the illuminating light. The search for the colors belonging to a same material begins by selecting one of the observed colors randomly. Membership of the colors in the considered region, the set $\{\mathbf{c}_i\}_{i=1}^n$, to the plane defined by the chosen color and the color of the illuminating light is expressed through the weights

$$w_i = \begin{cases} 1 & \text{if } |\mathbf{c}_i^T\mathbf{m}| < \varepsilon \\ 0 & \text{otherwise} \end{cases}, \tag{4}$$

where $\mathbf{m}$ is a unit vector normal to the plane and ε is a threshold value (Figure 2). In other words, if the distance of the color $\mathbf{c}_i$ to the plane defined by $\mathbf{m}$ is less than ε, it is assumed that $\mathbf{c}_i$ and the initially chosen color have been produced by the same material. From $\{w_i\mathbf{c}_i\}_{i=1}^n$, the dichromatic plane is re-estimated and the weights are computed again. This process is repeated until there is no change in the weights.

A candidate for the chromaticity of the diffuse reflection is estimated by assuming that for any discovered material there is a proportionally large number of colors having a chromaticity value similar to the actual body reflection's chromaticity. Under this assumption, the color of the body reflection of a material is estimated by looking for a radial cluster in RGB space. For a given discovered material, such a cluster may be found in the least squares sense as

$$\mathbf{b}_e = \arg \max_{\|\mathbf{b}\|=1} \sum_{i=1}^{n} \left(w_i \, \mathbf{c}_i^T \mathbf{b} \right)^2 . \tag{5}$$

Note that for a given $\mathbf{c}_i$, the quantity $(\mathbf{c}_i^T \mathbf{b})^2$ is maximum when $\mathbf{b}$ is parallel to $\mathbf{c}_i$. In matrix form, the expression of Equation (5) can be written as

$$\mathbf{b}_e = \arg \max_{\|\mathbf{b}\|=1} \|C\mathbf{b}\|^2 = \arg \max_{\|\mathbf{b}\|=1} \mathbf{b}^T C^T C \mathbf{b}, \tag{6}$$

where

$$C = \begin{bmatrix} w_1 \, \mathbf{c}_1^T \\ w_2 \, \mathbf{c}_2^T \\ \vdots \\ w_n \, \mathbf{c}_n^T \end{bmatrix} . \tag{7}$$

The solution to Equation (6) (the body color estimate) is given by the eigenvector associated with the largest eigenvalue of the 3×3 matrix $C^T C$. Observe that with this estimation criterion, which seeks to maximize the inner product of $\mathbf{c}_i$ and $\mathbf{b}$, the body color estimate will be pulled away from the actual body color and towards the color of the illuminating light if, among the considered colors, there are colors having a specular component (on the dichromatic plane, these colors reside on one side of the axis formed by the body color).

From matrix $C^T C$ it is also possible to estimate the plane (represented by a normal vector $\mathbf{m}$) that best fits all considered colors. Recall that this plane is needed in Equation (4) to re-estimate the weights indicating the membership of observed colors to a given material. To ensure that vector $\mathbf{m}$, being the normal vector to a dichromatic plane, is perpendicular to the color of the illuminating light, $\mathbf{m}$ is written in terms of a vector $\mathbf{u}$ laying on the subspace that is orthogonal to $\mathbf{s}$:

$$\mathbf{m} = [\mathbf{w_1} \; \mathbf{w_2}] \, \mathbf{u}, \tag{8}$$

where $\mathbf{w_1}$ and $\mathbf{w_2}$ are an orthonormal basis of the subspace. Substituting $\mathbf{m}$ for $\mathbf{b}$ in Equation (6) and rewriting the equation as a minimization problem, the normal vector defining the sought plane is given, through Equation (8), by the eigenvector associated with the smallest eigenvalue of the matrix $[\mathbf{w_1} \; \mathbf{w_2}]^T C^T C \, [\mathbf{w_1} \; \mathbf{w_2}]$. This vector seeks to minimize, for all considered colors, the product $(\mathbf{c}_i^T \mathbf{m})^2$ constrained to $\mathbf{m}$ being perpendicular to $\mathbf{s}$ (a quantity that for a single $\mathbf{c}_i$ is minimum when $\mathbf{m}$ is perpendicular to $\mathbf{c}_i$).

Note that assigning a weight to each color is, in essence, segmenting the image. But also note that this segmentation is carried out using color information alone, which, contrary to previously proposed approaches, involves no special spatial coherence between considered pixels, other than being taken from some region of the image.

In an image showing small isolated material patches, a single type of reflection is most likely to remain dominant throughout any given patch. When the dominant type of reflection in a patch is specular, an estimate of the body color for the patch would be more reliable, it is argued, if purely diffuse colors of the material were, somehow, available in addition to the colors of the patch. In general, a natural scene has a set of colors clustering around the body reflection of each observed material [6]. By considering image colors irrespective of how they may be arranged in the image plane, the approach proposed here seeks to seize the largest possible number of image colors forming the body cluster of the material. Note, however, that the approach of this section will fail if, for instance, in the considered region there are two materials whose actual body colors are coplanar with $\mathbf{s}$. The approach will find a single material and, in turn, a single body color for both materials.

Experimental Results

Given an RGB image and the color of the light that illuminated the scene, the specular-free image is obtained by locally inspecting the image. To determine the body color of the image at a given pixel location, the colors within a square region (a window) centered at that pixel location are considered. The number of different materials and their corresponding dichromatic planes are first identified using the procedure introduced in the section on *Finding Body Colors*. Among the discovered materials, only the colors from the material whose dichromatic plane is closest to the color of the given pixel are further considered. A body color estimate for the material is obtained, and the specular-free color of the image at the given pixel location is calculated using the projection scheme laid out in the *Removing Specularities* section.

There are two parameters affecting the performance of the technique: the size of the square window used to explore the colors of the scene, and the threshold ε of Equation (4) used to distinguish the different materials that may coexist in the considered square region. With these two parameters in mind, the experimental results shown in this section were aimed at visually assessing the performance of the proposed technique. Both synthetic and real images were used.

In Figure 3(a), the synthetic image of a sphere is shown. In this image, two different materials are observed: one that covers a large portion of the sphere, and another that covers five small patches around the center. Note that the specular reflection dominates in one of such patches. The specular-free image of Figure 3(b) was obtained by inspecting the whole image for any considered image pixel. All small patches in the image have the same body color, and this color is similar to the body color of the small patches in the image of Figure 3(a). When a window covering a fraction of the total image's area was used, the discovered body color varied. The estimated body color was "lighter" the closer the considered pixel was to the highlight's brightest point. This is naturally anticipated since the body color estimate (given by Equation (5)) of a surface showing both specular and diffuse reflection is, to some degree, biased towards the color of the light. The fewer body colors there are, the stronger the bias.

Figure 3(c) shows an image taken from the *specular* subset of the Simon Fraser University dataset for color research [2]. In this dataset, information on the RGB color and the spectral content of the set of illuminants used is also included. Figure 3(d) shows a specular-free image recovered using the proposed approach. Observe that in this image surfaces are not as shiny as

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the surfaces in the original image. This image was obtained by using a window covering a ninth of the total image's area and a gap (Figure 2) with $\varepsilon = 20$. When a narrower gap was used, within some objects, patches of a "lighter" color tended to appear. When a broader gap was used, the discovered body colors tended to be a "blend" of the different colors in the image. Nevertheless, the general aspect of the recovered specular-free image remained somewhat similar to that of the image shown in Figure 3(d). The gap is used to account for noise and other sources of errors that may cause the observed colors to depart from the dichromatic planes of the scene. With a narrow gap, colors emanating from the same material may be classified as belonging to a different material; with a broad gap, colors emanating from different materials with relatively similar properties may be seen as produced by a single material. Clearly, a variation in ε produces a variation in both the number of discovered materials and their corresponding body color estimates.

Conclusions

An approach to recover from a single RGB image a specular-free image was proposed. It was assumed that the color of the illuminating light is known. Contrary to previously proposed approaches, the method proposed in this paper was derived by making no strong spatial connectivity assumption of pixels properties. The performance of the proposed technique was tested on synthetic and real images, showing promising results.

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(a) (b)

(c)

(d)

Figure 3. *Experimental results. Figure (a) shows a synthetic image of a sphere made of two different materials. Figure (b) shows the specular-free image obtained by analyzing, for any given pixel location, all observed colors. All the small patches of this image have the same body color. Figure (c) shows an image taken from the* specular *subset of the Simon Fraser University dataset. Figure (d) shows the recovered specular-free image. Note that surfaces in this image do not look as shiny as the surfaces of the image in Figure (c).*