Saturation-preserving Specular Reflection Separation

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Specular reflection generally decreases the saturation of surface colors, which will be possibly confused with other colors that have the same hue but lower saturation. Traditional methods for specular reflection separation suffer this problem of hue-saturation ambiguity, producing over-saturated specular-free images. We proposed a two-step approach to solve this problem.

In the first step, we produce an over-saturated specular-free image by global chromaticity propagation from specular-free pixels to highlighted ones. Traditional methods propagate the chromaticity between adjacent pixels [3], which will be blocked by color discontinuities. The chromaticity cannot be transferred from the specular-free regions to the isolated highlight regions, so there will be residual specular reflection left in the recovered specular-free image. See the green patch in the middle of Fig. 1 (e) for an example. Our global propagation can overcome this problem (Fig. 1 (g)). We show in this paper that the full propagation of chromaticity ensures a good start point to recover the saturation.

In the second step, we recover the saturation based on priors of the piecewise constancy of diffuse chromaticity as well as the spatial sparsity and smoothness of specular reflection. We achieve this through increasing the achromatic component of diffuse chromaticity, while the magnitudes of increments are determined by linear programming under the constraints derived from the priors. See Fig. 1 (c) for an example.

According to the dichromatic reflection model [2], an image with both diffuse and specular reflection can be represented as:

$$\mathbf{I}(p) = m_d(p)\mathbf{\Lambda}(p) + m_s(p)\mathbf{\Gamma} \quad (1)$$

where $\mathbf{\Lambda}$ is the chromaticity of diffuse reflection and $\sum_{i\in\{r,g,b\}}\mathbf{\Lambda} = 1$. $\mathbf{\Gamma}$ is the chromaticity of the illumination. The color of specular reflection equals the color of the illumination. Without loss of generality, we assume that the illuminations are always white, so $\mathbf{\Gamma}$ is a constant vector $[1/3, 1/3, 1/3]^T$. Highlight removal aims at reducing m_s to 0 for each pixel.

Hue-saturation Ambiguity. Specular reflection changes the saturation of the surface color while retaining their hue [3]. Thus specular reflection generates a set of hue-equivalent classes $\mathcal{H}$, i.e., colors with same hue but different saturation. Note that, surface colors with the same hue will fall into the same class with those produced by specular reflection. To reveal the hue-equivalent class, we rewrite Eqn. 1 to be:

$$\mathbf{I}(p) = m_l(p)(t(p)\mathbf{\Lambda}(p) + k(p)\mathbf{\Gamma}) + \tilde{m}_s(p)\mathbf{\Gamma} \quad (2)$$

where m_l is the illumination, t is intensity of the chromatic part of the diffuse reflection, k is the intensity of the achromatic part of the diffuse reflection, $\tilde{m}_s$ is the **pure specular reflection** without any residual of the achromatic part of diffuse reflection. Note that $\tilde{m}_s$ depends on m_l, but the dependency will not affect the analysis following Eqn. 2, so we do not write it explicitly. Each $\mathbf{\Lambda}$ defines a hue-equivalent class $\mathcal{H}(\mathbf{\Lambda})$ with varying t and k. All the pixels $p \in \mathcal{H}(\mathbf{\Lambda})$ can be represented by the same form of Eqn. 1 after the following transformations:

$$m_d = m_l t, \quad m_s = \tilde{m}_s + m_l k = \tilde{m}_s + m_d r \quad (3)$$

where $r(p) = k(p)/t(p)$ measures the ratio between the achromatic and the chromatic part of the diffuse reflection. Note that the specular reflection m_s will contain a portion of diffuse reflection when r is non-zero.

Our goal is to get the pure specular reflection $\tilde{m}_s$. We separate the whole process into two simpler stages: (1) Searching the diffuse chromaticity $\mathbf{\Lambda}$ for each hue-equivalence class through hue-based affinity propagation, from which we can get the diffuse reflection m_d and specular reflection m_s; and (2) Recovering the pure specular reflection $\tilde{m}_s$ through removing the achromatic part of diffuse reflection out of m_s.

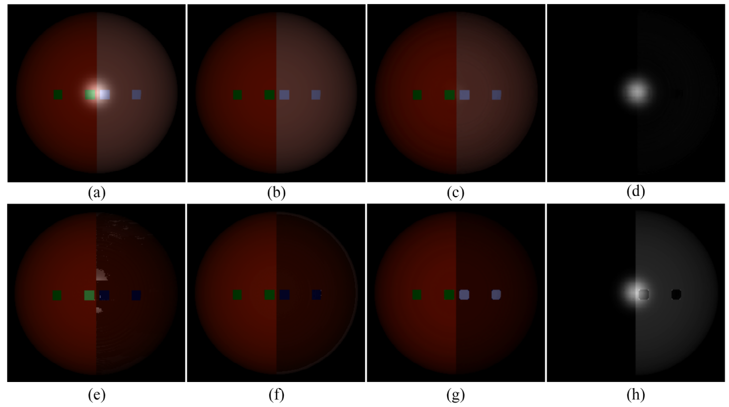

Figure 1: Specular reflection separation. (a) Input image. (b) Ground-truth specular-free image. (c-d) The recovered specular-free image and specular reflection by our method. (e) The result of [3]. (f) The result of [4].(g-h) The result of the first stage of our method: global propagation of diffuse chromaticity among pixels with the same hue.

We use Affinity Propagation (AP) [1] to cluster the pixels into hue-equivalent classes and determine the diffuse chromaticity $\mathbf{\Lambda}$ by the chromaticity of their specular-free anchor points. AP determines the optimal number of clusters automatically, which is suitable for handling images that the number of distinct hues are unknown.

AP requires two types of inputs: the affinity between each pair of pixels and the preference of each pixel to be an anchor point. The affinity is set to be the similarity of hue and the preference is an increasing function of the saturation. AP encourages the anchor points to fall at pixels which are most probably to be specular-free. Meanwhile the other pixels will be assigned to the clusters that form the hue-equivalent classes.

After we got the diffuse chromaticity $\mathbf{\Lambda}$, we can get m_s and m_d according to Eqn. 1. We formulate the inference of r as the following energy minimization problem:

$$\begin{aligned} &\arg\min_r E_{data}(r) + w_d E_d(r) + w_s E_s(r) \\ &\text{s.t. } 0 \le r(p) \le m_r(p), \forall p \end{aligned} \quad (4)$$

The three energy terms are derived from the spatial sparsity of specular reflection, the piecewise constancy of diffuse chromaticity, and the smoothness of specular reflection, respectively.

The lower bound is derived from the fact that we produced an over-saturated specular-free image in the first stage while the upper bound is got from $\tilde{m}_s \ge 0$. These bounds are important for finding the optimal solution of the optimization problem.

Our conclusion is that through explicitly modeling the chromatic and achromatic part of the diffuse reflection, our model can separate the specular reflection while preserving the saturation of the underlying surface colors.

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This is an extended abstract. The full paper is available at the Computer Vision Foundation webpage.