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Specularity removal: A global energy minimization approach based on polarization imaging

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ABSTRACT

Concentration of light energy in images causes strong highlights (specular reflection), and challenges the robustness of a large variety of vision algorithms, such as feature extraction and object detection. Many algorithms indeed assume perfect diffuse surfaces and ignore the specular reflections; specularity removal may thus be a preprocessing step to improve the accuracy of such algorithms. Regarding specularity removal, traditional color-based methods generate severe color distortions and local patch-based algorithms do not integrate long range information, which may result in artifacts. In this paper, we present a new image specularity removal method which is based on polarization imaging through global energy minimization. Polarization images provide complementary information and reduce color distortions. By minimizing a global energy function, our algorithm properly takes into account the long range cue and produces accurate and stable results. Compared to other polarization-based methods of the literature, our method obtains encouraging results, both in terms of accuracy and robustness.

1. Introduction

Based on the dichromatic reflection model (Shafer, 1985), each brightness value in an image is viewed as the sum of two components, the diffuse and the specular parts. Most opaque surfaces have a combination of specular and diffuse elements due to surface structure. The diffuse element is viewable from all directions while the specular part behaves based on Snells law (Morel et al., 2005), so is only visible when viewed from the correct orientation. The specular reflection appears to be a compact lobe on the object surface around the specular direction, even for rough surfaces (Nayar et al., 1997). Whereas the diffuse component represents the actual appearance of an object surface, specularity reflection is an unwanted artifact that can hamper high-level processing tasks such as visual recognition, tracking, stereo reconstruction, objects re-illumination (Godec et al., 2013; Hosni et al., 2013). Specularity removal, a challenging topic in computer vision, is thus a decisive preprocessing for many applications (Artusi et al., 2011).

1.1. Related works

The light reflection always carries important information of a scene, so that the separation of the reflection gives a way to better analyze the scene. Nayar et al. (2006) separates the reflection using structured light, which conveys useful properties of the object material as well as the media of the scene. O'Toole et al. (2016) also use structured light in reflection separation to recover the 3D shape of the object. While the above methods have shown good performance in their applications, they analyze the scene through the direct and global reflection components, whereas we analyze it through the specular and diffuse reflections. Direct components contain both specular and diffuse reflections, while global components arise from interreflections as well as from volumetric and subsurface scattering. The direct/global separation handles complex reflections, which may result in useful material related information ; however it requires strict controllable light source, which limits this usability of this separation. On the other hand the specular/diffuse component analysis deals with natural light source, which makes it more valuable. The separation of specular/diffuse components is thus regarded as pre-processing step, since specular reflection might be problematic in several computer vision tasks, such as stereo matching, image segmentation or object detection.

There are also works that aim at separating the diffuse and specular components under polarized light source. For instance, in Kim et al. (2016) a robust diffuse/specular reflection separation method is proposed, but is designed to only work for scene under controllable light source. In this work, we take a different approach leading to a generalization of the applicability: we deal with scenes

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under uncontrollable light source, in order to imitate outdoor illumination conditions.

Traditional methods separate the diffuse and specular components using color-only images, based on the idea to find a variable which is independent from the specular component. By estimating this variable for each given pixel, the diffuse component may be computed. As a seminal work in color-based methods, Tan et al. (2004) inspects the specular component via chromaticity, which is proved to be independent from the specular component. An additional hue-based segmentation method is required for the multi-colored surfaces. Yang et al. (2013) extend this work by detecting diffuse pixels in the HSI space, which also requires hue-based segmentation. The color covariance is defined as a constant variable to recover the diffuse component. Kim et al. (2013) use the dark channel prior as a pseudo-solution and refine the result through the Maximum A Posteriori (MAP) estimation of the diffuse component. The dark channel prior, however, only works for highly colored surfaces. To avoid extra segmentation, Tan and Ikeuchi (2005) propose another diffuse pixel pick-up method via computing the logarithmic differential between up to four neighboring pixels. The common limitation of the above presented color-based methods is their high color distortion on the recovered diffuse component (Nayar et al., 1997; Tan and Ikeuchi, 2005; Yang et al., 2013). The main reason is that these methods assume that the specular color is constant throughout the image.

To better recover the diffuse component, other methods proposed to accomplish the separation using polarization images (Wolff and Boult, 1991), since specular and diffuse components hold different degrees of polarization (DOP). The DOP represents the ratio of the light being polarized. When a beam of unpolarized light is reflected, the DOP of specular reflection is larger than that of the diffuse reflection for most angles of incidence, meaning that the specular reflection is generally much more polarized than the diffuse reflection (Born and Wolf, 1999). When rotating the polarizer, the change of the intensity is only related to the specular part, so that the intensity change refers directly to the specular color.

With these constraints, polarization based methods produce more accurate results with less color distortions. The pioneering work of Nayar et al. (1997) constrains the diffuse color on a line in RGB space. The neighboring diffuse-only pixels are used to estimate the diffuse component, providing state-of-the-art polarization-based specularity removal results. However, specular pixels are detected by simple thresholding of the DOP. The DOP changes not only with different specular portions, but also with different incident angles and different indices of refraction. The computation of the DOP involves more than three images, making it largely contaminated by camera noise. This makes Nayar's method prone to error since its computation highly relies on the DOP.

The methods presented above are local and based on the dichromatic reflection model (Shafer, 1985). These methods assume that the intensity of a pixel is a linear combination of its diffuse and specular components. On the other hand, a global-based method presented in Umeyama and Godin (2004) simplifies this model into the image level, under the conditions that the light source is far away from the object and that the incident angle does not change. In other words, the acquired image is linearly combined by a specular image and a diffuse image with respect to a constant parameter. This parameter is reversed using the Independent Component Analysis (ICA) (Hyvärinen et al., 2004). However, these ideal conditions discussed in Umeyama and Godin (2004) rarely conform to reality, thus only a part of the specular reflection component is removed.

With respect to the literature, we make the following observations: (i) color-based methods produce heavy color distortions; (ii) local patch-based methods can only use the information offered by neighboring pixels without any consideration of long range cues. Based on these observations, we proposed in this article a global method using the polarization setup and a local approximate solution as detailed in the next subsection.

1.2. Contribution

Our approach builds upon Umeyama's method (Umeyama and Godin, 2004) and share conceptual similarities. However, we propose a threefold contribution: (i) As in Umeyama and Godin (2004) we assume that the acquired image is the linear combination of a diffuse and specular reflection images. However, we depart from the use of a fixed weighting coefficient and instead investigate the benefit of using a spatially varying coefficient, which generalizes the model proposed in Umeyama and Godin (2004) to better conform to the reality. The use of the spatially varying parameter additionally enables the algorithm to work with scenes under (non-overlapping) multi-sources of illumination. (ii) Based on these assumptions, a global energy function is constructed to leverage long range information, that patch based method cannot handle, by construction. In patch based methods, the solution for one pixel is influenced only by the local neighborhood. In a graph based approach, pixels are connected through the graph construction, and their interdependency is accounted thanks to the smoothness term; additionally, the graph energy is minimized globally. The expectation is that by optimizing the problem globally, results will be more accurate and robust than with local patch-based methods. The optimum solution is found by applying the graph cuts algorithm (Boykov et al., 2001). (iii) Apart from the independence assumption, a first approximate solution is computed as a supplementary constraint. We propose to compute a more reliable approximate solution by combining the specular detection method in Tan and Ikeuchi (2005) and the specularity reduction in Nayar et al. (1997). Lastly, in the experimental part, a histogram-based criterion is proposed to quantitatively evaluate the results. The proposed method is compared with two well-known separation algorithms : Nayar's polarization setup (Nayar et al., 1997) and Umeyama's method (Umeyama and Godin, 2004). This paper extends upon our previous preliminary work (Wang et al., 2016) in the following aspects. In the current paper, we fully elaborate on the idea and the steps of the computation of the first approximate solution. The computation of the data term is accurately described, as well as the smoothness term, and the justification as to why the solution is ensured to be stable. This paper contains some additional illustration to demonstrate more clearly the improvement of the proposed global method. Supplementary experiments are also reported, including the study of the algorithm robustness in the presence of noise.

1.3. Overview

In the remainder of the paper, we first present our polarization system in Section 2. The problem formulation is defined in Section 3. In Section 4, we describe the proposed global energy function, and explain each term in detail. In Section 5, we describe the implementation of the method with a discussion about the results. Finally, we offer some perspectives to this work in Section 6.

2. Polarization system

The light reflection from an object is a combination of diffuse and specular components, in which the specular component is generally partially linearly polarized. It is fully described by three parameters (Ainouz et al., 2013): light magnitude I, degree of polarization ρ, angle of polarization φ. In order to measure the polarization parameters, a polarizer rotated by an angle α is installed