Fast Separation of Reflection Components and its Application in 3D Shape Recovery

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Abstract

In this paper we present a fast and robust method to separate reflection components in color images. Thus the method is also suitable for various industrial and scientific applications. The technique operates with a two-dimensional color representation. Furthermore, we show that our approach improves the experimental results of a fast three-dimensional surface reconstruction scheme.

Introduction

The separation of reflection components plays an important role in two-dimensional image processing as well as in three-dimensional interpretation of objects. Currently, the existing techniques are mostly time consuming and thus seldomly applied. The separation of reflection components is necessary for instance in physically based image segmentation, feature extraction, object recognition, and in almost all three-dimensional approaches, such as binocular stereo, motion from optical flow, shape-from-shading, and active range scanners. For modelling the reflection it is usual to use an additive composition of two reflection components, the interface reflection $L_{x,s}$ (specular) and the body reflection (matte) $L_{x,b}$ at each image location x. We will call materials with such reflection characteristics hybrid materials. Shafer[1] combines this with RGB-color information in the Dichromatic Reflection Model (DRM):

$$L_x = L_{x,s} + L_{x,b} = c_{x,s} m_{x,s} + c_{x,b} m_{x,b}.$$

Here, $\mathbf{c}_{x,s}$ and $\mathbf{c}_{x,b}$ are the interface and body reflection color vectors, respectively, $m_{x,s}$ and $m_{x,b}$ are geometrical scaling factors. We use this model in our separation technique. Later on, from $m_{x,b}$ the surface shape is recovered. In general, $m_{x,s}$ is assumed to be the illumination color (neutral interface reflection model)[2]. In general, for objects with curved shape the RGB-colors are dense clusters. For partially curved or polyhedral objects there are gaps in the clusters. Among other things these gaps complicate a three-dimensional analysis of the RGB-space of scenes with more than one surface material[3]. Instead of using a three-dimensional color representation we analyze two-dimensional chromaticity diagrams of the image.

Separation of Reflection Components

In our approach we use the normalized u and v values of an $Y'U'V'$-space, the uv-chromaticity. The $Y'U'V'$-space is defined as follows:

$$(Y', U', V') = (R, G, B)\begin{pmatrix} \frac{1}{3} & \frac{1}{2} & \frac{-1}{2\sqrt{3}} \\ \frac{1}{3} & 0 & \frac{1}{\sqrt{3}} \\ \frac{1}{3} & \frac{-1}{2} & \frac{-1}{2\sqrt{3}} \end{pmatrix}.$$

Surfaces of ideal matte materials correspond to exact one point in the uv-space. Therefore, the dichromatic matte cluster (with or without gaps) corresponds to one point, too. Dichromatic highlight clusters without gaps form line segments in the uv-space. These line segments start at the point representing the matte cluster and follow the direction to the color of illumination which is represented by another point. Due to the additive composition these line segments do not reach the illumination color. If the highlight cluster contains gaps the corresponding line in the uv-space contains gaps, too. It will become clear later that this does not cause any problems for the analysis. The theory of a generic chromaticity model (which includes the uv-space) for reflection analysis is described in previous paper in detail[4]. Figure 1 illustrates the structure of dichromatic clusters in uv-space and shows the clusters of one matte and of three hybrid surfaces.

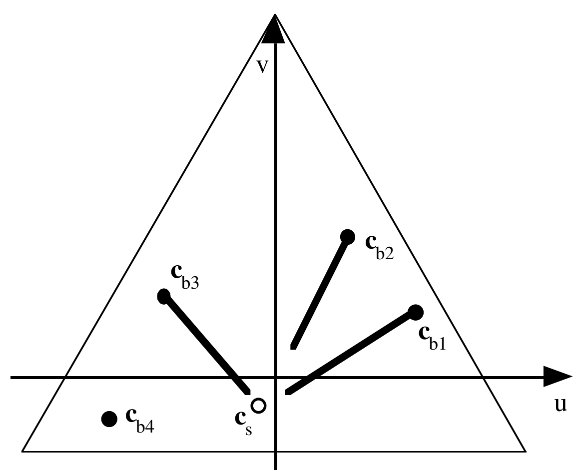

Figure 1. 1-3 h, 4 m configuration

Hue Space

Additionally, we use an one-dimensional hue space (h-space) containing the number of pixels per angle α, where α is an angle in the uv-space between two lines. One is the line passing through the chromaticity of the illumination color and the chromaticity of the pixel color. The other one passes through the chromaticity of the illumination color and a defined fix point. The defined fixed point in the uv-space can be each value except the illumination color, but it must be a constant fixed point for the whole image.

Morphological Filters

In our technique we look for maxima twice. To avoid problems with different levels of maximum values we work with the following one-dimensional discrete morphological filter[5]:

$$g(x) = f(x) - max\begin{Bmatrix} m_i : -p \leq i \leq p \ \text{ and} \\ m_i = min\{ f(j) : -p-i \leq j \leq p+i \} \end{Bmatrix},$$

where $f(x)$ is the original function and $g(x)$ is the result of morphological filtering. In our realization, the parameter p is set to 1. We also assume that if $f(x)$ is undefined, then $f(x)$ is set to 0.

Matte Color Estimation

At first, each measured 3D-color vector is transformed to the uv-space and then to the h-space. Then, the h-space is transformed with a morphological filter as described above. This data set is searched for maxima. For each maximum $m_h = h(\alpha)$ found in the h-space, a maximum $m_{uv} = uv(h(\alpha))$ in the uv-space is searched along line l_α referring to the actual α. Due to the DRM, we have to look along line l_α for a uv-space value v>0 with the maximal distance to illumination color. To reduce noise influence we combine this by seeking a frequency maximum. If there is more than one local maximum, then materials exist in the scene that have the same hue value but different saturations. In this case the RGB-colors lying on the line l_α must be rotated in the plane spanned by the 3D counterpart of the line l_α and the origin. This keeps the analysis in two dimensions. Each value m_{uv} is a matte color and the number of maxima gives the number of different materials in the scene.

The approach assumes, that the pure matte color is visible in the scene, i.e. there must be at least one image point with no specular reflection for each hybrid material.

Segmentation

To eliminate highlights (the specular component) we must know two reflection components, described above, for each pixel in the image. The body reflection components are determined with the procedure described above, but to take the right body color for each pixel, we have to segment the image physically. To reach this, we only need to segment the h-space. This is straightforward, since the h-space is one-dimensional.

The interface component is assumed to be constant over the scene. If there are more than one hybrid material, the illumination color can be estimated from the image (for example [2]), otherwise the color must be estimated separately.

Highlight Elimination

As a result of matte color estimation and segmentation both vectors of the DRM are known. Highlights are eliminated by setting the geometrical scaling factor $m_{x,s}$ of the interface reflection color to zero. This is due to the fact that colors in the DRM are represented as a linear combination of a body reflection and the interface reflection color.

Applications of the Technique

The above approach can be used in different fields of color image processing. The algorithm is fast and the results are accurate. To demonstrate the performance we apply the matte reflection component to the Photometric Stereo Method (PSM)[6]. PSM calculates surface shape (via computing from its orientations) from the shading variations in three images, taken of the objects with the light source in different positions and consecutive illumination. From the surface orientations the depth can be calculated using an integration technique. Comparisons with several approaches have shown, that a FFT-based method[7] produces the best results. We conjecture that PSM is a good candidate to evaluate the performance, because PSM only works with matte (Lambertian) images. In Section 5 we show some PSM results with and without reflection component separation. Using our separation technique the geometric information of the 3D-objects calculated from the PSM images can be combined with photometric and colorimetric attributes. Since PSM additionally recovers surface albedo values, illumination independent surface color descriptors can be obtained. From these color descriptors a set of CIE tristimulus values can be assigned to each surface element[8-10] without using a spectro-radiometer. Moreover, from the separated specular reflection component and the surface orientations it is possible to extract roughness values of uniform colored surface regions[11].

Time Efficiency

The developed techniques are conceived in such a way that they can be realized very time efficient. The color transformation to chromaticity values is supported by most of the framegrabber boards. The color analysis is performed in a two-dimensional space. In comparison, approaches using unnormalized color need a principal component analysis[3] or a Singular Value Decomposition. The matte image generation is a simple coordinate transformation. The surface orientations can be calculated with a three-dimensional linear mapping or our albedo-independent lookup table method. The integration of the surface orientations is FFT-based and can be calculated with an FFT-board. The whole shape recovery process takes less than ten seconds on a Sparc 10 (with no support of special hardware).

Results

We have tested the techniques with several synthetic and real object scenes. Due to lack of space we show only a few results of real images. For image generation the gain control and the gamma correction was turned off. Since the dynamic range of CCD-cameras is strongly limited it is expedient to combine images with different irises to avoid clipping and pre-kneeing. Since the analysis is done in chromaticity space, for the proposed techniques there is no special treatment necessary. The objects were illuminated with a slide projector. The highlight elimination method can handle scenes illuminated with more than one source, but such images are not useful for the PSM application. Figure 3 shows the image of a multi-colored plastic sphere with highlights in the red and magenta region.

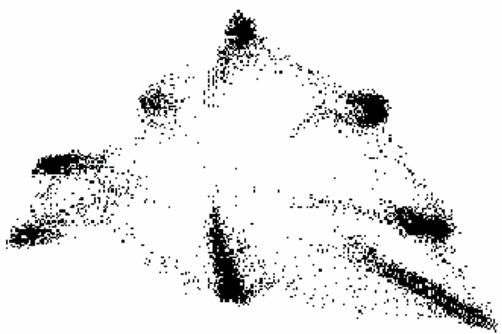

Figure 2. Chromaticity representation of the sphere.

Figure 2 shows the used chromaticity representation of the sphere. Figure 4 is the false color representation of the segmentation of the proposed technique. White pixels identify regions left unsegmented. A unique matte color is assigned to each segmented region. The green region is not completely segmented, since the intensity is too low to assign matte chromaticities. These gaps cause no problems with the matte image generation, since dark regions are not affected by highlights. In Figure 5 the generated matte image of the sphere is shown. Tab. 1 shows the estimated matte color vectors, the normalized true (manually measured) RGB vectors, and the angular deviations of the sphere.

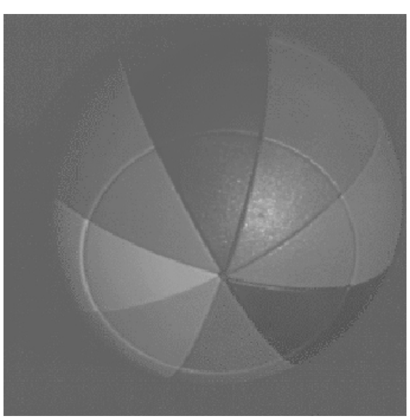

Figure 3. One of three input images of a multi-colored sphere

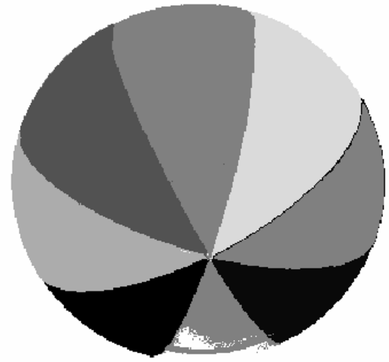

Figure 4. Physically based segmentation (false color representation) of the sphere using the proposed method.

Figure 6-8 illustrate the influence of highlights on surface reconstruction. Figure 6 shows one of three input images for the Photometric Stereo shape recovery technique. On the watering can (without its spout) the highlight area is quite large. Figure 7 shows the rotated reconstructed surface. A texture mapping (original image) is applied to the range data. The reconstructed watering can is strongly deformed. The highlight locally causes a dent. The result of surface reconstruction using three matte images obtained with our technique is shown in Figure 8. The matte image is mapped onto the range data. Note that the positions of camera and object are fixed during image acquisition and only three different illumination directions are used.

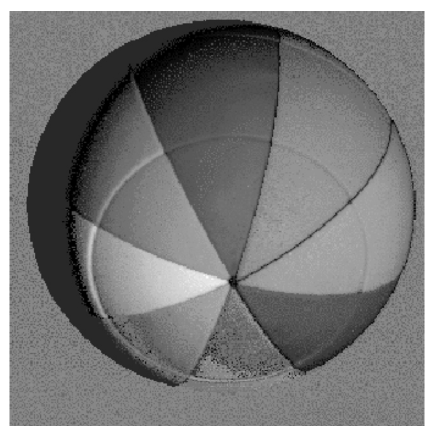

Figure 5. Sphere image after highlight detection andelimination.

Conclusion

We have developed a new two-dimensional method for separating reflection components using a chromaticity analysis rather than a three-dimensional one, so far commonly used. This approach has several advantages. It is less geometry dependent. It facilitates the treatment of more than one hybrid material in the scene. It can be realized with existing hardware components. The quality of the results has been demonstrated by applying the matte reflection component to a shading based shape recovery scheme. The techniques developed here are suitable for industrial and scientific applications.

Table 1. Estimated and true body reflection colors as well as the angular deviations of the sphere with eight different colors.

estimated normalized RGB values	true normalized RGB values	deviation in degree
0.285 0.505 0.210	0.284 0.505 0.211	0.131
0.485 0.402 0.113	0.481 0.401 0.118	0.526
0.631 0.250 0.119	0.635 0.242 0.123	0.804
0.726 0.138 0.136	0.720 0.137 0.143	0.613
0.441 0.170 0.390	0.443 0.168 0.389	0.279
0.176 0.244 0.580	0.170 0.243 0.587	0.719
0.158 0.333 0.509	0.154 0.331 0.515	0.630
0.236 0.409 0.355	0.233 0.414 0.353	0.588

Figure 6. Input image of a watering can (without spout).

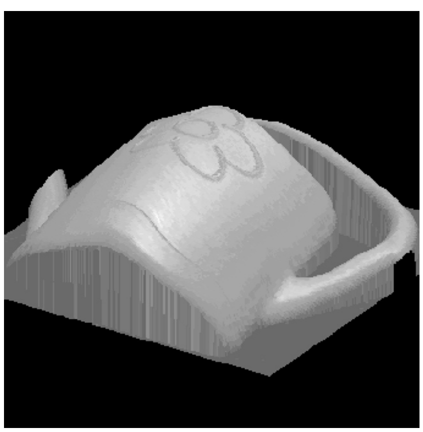

Figure 7. View of 3D reconstructed watering can using Photometric Approach without highlight elimination.

Figure 8. View of 3D reconstructed watering can using Photometric approach with highlight elimination.

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