Analysis of Multiple Reflection Components

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ABSTRACT — **In this paper we propose an algorithm for detection and separation of specularity from Lambertian reflectance using multiple image frames from different viewpoints. The algorithm is based on the physical model of multiple reflection mechanism that the appearance of specularity varies depending on viewing direction while that of Lambertian reflection does not. Our approach is to move camera sensors actively and to obtain as many image frames as possible. With known positions of sensors, we use a reconstruction algorithm similar to the computerized tomography to obtain object structure as well as to identify multiple reflection components regardless of material types. Experimental results are presented to show the efficiency of our algorithm.**

1 Introduction

Recently there has been a growing interest in the visual measurement of surface reflectance properties in both basic and applied computer vision research. Most vision algorithms are based on the assumption that visually observable surfaces have only Lambertian reflection properties. Specularity is one of the major hindrances to vision tasks such as image segmentation, object recognition, and shape or structure determination. Without any means of correctly identifying reflectance types, image segmentation algorithms can be easily mislead into interpreting specular highlights as separate regions or as different objects with high albedo. Algorithms such as shape from shading and structure from stereo or motion can also produce false surface orientation or depth from the non-Lambertian behavior of specularity. Therefore it is desirable to have algorithms for estimating reflectance properties as a very early stage of many visual processes. In numerous industrial applications, there is also great demand for visual inspection of surface reflectance which is directly related to surface polish and paint quality.

Although the measurement of surface reflectance properties has been the topic of many research efforts in applied physics, only a few attempts in computer vision have been made until recently. There have been photometric-stereo-type approaches to the measurement of reflectance properties and surface orientation by Coleman and Jain [2], and by Nayar, Ikeuchi and Kanade [3]. Wolff proposed a method using analysis of polarization of reflected light [4]. There have also been approaches using color by Klinker, Shafer and Kanade [5], and more recently by Bajcsy, Lee and Leonardis [1].

Although all the approaches mentioned above are based on physical models of reflection mechanisms, they have restrictions in applications. The basic technique with the photometric-stereo-type approaches is the control of illumination. Therefore the application is limited to the environments where the illumination can be strictly controlled. The polarization approach also has restrictions on illumination. The color approaches are based on two assumptions. One is that object surfaces consist of only colored dielectrics. The other is that object surface reflectance is spatially piecewise uniform. The second assumption makes it possible to use the region information for separating specular and Lambertian reflectances, and is also required for the polarization approach.

In this paper we propose the use of many images with different views not only to separate specularity from Lambertian reflectance but also to obtain object structure. Our algorithm is based on the fact that, unlike Lambertian appearance, the appearance of specularity varies depending on the viewing direction. With active control of camera sensors, our algorithm does not require the controlled illumination or the restriction on the material types such as metals and dielectrics or on the spatial variation of surface reflectance. We describe our model of multiple reflection components, and present a reconstruction algorithm for obtaining object structure and for separating different reflection components.

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2 Reflectance Model

Our work is based on the following model of reflectance mechanisms. There are two physically different types of reflectance [6]. When light reaches an interface between two different media, some portion of the light is reflected at the boundary (interface reflection). The remaining portion passes through the boundary and interacts with internal pigments. The light is reemitted randomly and thus has the Lambertian property (body or sub-surface reflection). Dielectrics have both interface and body reflection while metals have only interface reflection. Surfaces having only Lambertian reflectance component look equally bright from all directions, that is, the brightness does not depend on viewing direction. Specularity results from interface reflection and the reflected direction of the specularity depends on the illumination direction and surface orientation. The specularity is diffused depending on the surface roughness. Highly polished surfaces have sharp specularity which is called specular spike. As surfaces are roughened, the specularity is diffused and it is called specular lobe.

The fact that the interface and Lambertian reflections are often spectrally different is key to separation by color. In [1] we proposed a computational model using color for separating specular and Lambertian reflection based on the physical properties of sensors and surface reflectances. Our model allows us to separate diffuse as well as sharp specularities from Lambertian reflections. Therefore inter-reflections between adjacent objects (which are usually diffused) can also be detected. The proposed algorithm in this paper uses the Lambertian property that the appearance of Lambertian reflection does not vary depending on viewing direction (Lambertian consistency). On the other hand, the specularity is dependent on the viewing direction whether diffused or not.

3 Structure Perception from Multiple Reflections

The specular reflection is a mirror reflection and has different mechanisms from the one of the Lambertian reflection. In Figure 2 (a), specular reflection is illustrated for a 2-dimensional convex mirror. The direction of specular reflection follows the law of reflection such that the incidence angle is equal to the exitant angle and that the incident ray and reflected ray lie in the plane containing the surface normal. From the geometrical optics, the focus of the mirror reflection is given by

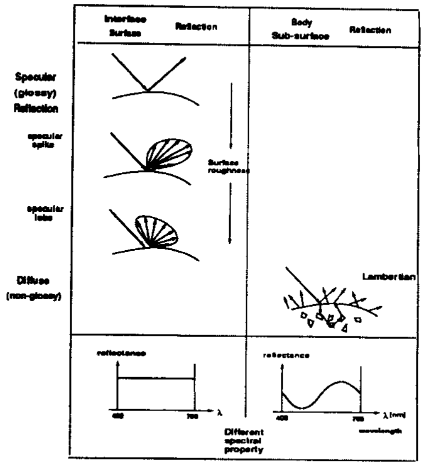


Figure 1: Reflectance model

$$f = \frac{R}{2} \cos\beta, \tag{1}$$

where R is the curvature (positive for convexity and negative for concavity) and β is the incidence angle. The trajectory of the focus for a distant point light source and for a wide angle of views is shown in Figure 2 (b). The mechanism of perceiving object shape from specularities is different from the one from Lambertian reflections. If we perceive the shape of an object by specularities in a Lambertian sense, the shape would be the trajectory of the focus which we call specular structure. The specular structure is closer to the Lambertian structure when the curvature is higher or the incidence angle β is close to 90°.

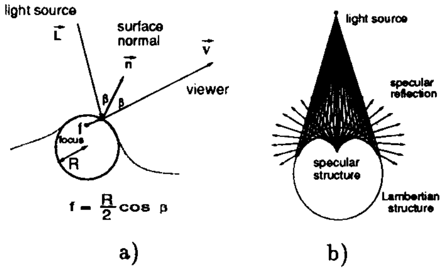


Figure 2: (a) Specular reflection (b) Specular structure

We now establish a model for shape perception from multiple reflection components. A Lambertian reflector can be regarded as a spatially fixed source of light that is omnidirectional. On the other hand, a specular reflector changes its position depending on viewing direction and the direction of reflection depends on the surface normal and illumination direction. Figure 3 shows our model for the specular and Lambertian reflectors as light sources. Since the specular and Lambertian reflections are linearly added in observation they are transparent to each other. On the other hand Lambertian reflectors are opaque to other Lambertian reflectors, causing occlusion.

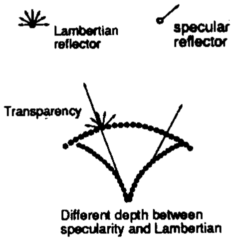


Figure 3: Model for multiple reflections

4 Reconstruction of Structure from Multiple Reflectances

In designing an algorithm for detecting specularities by their variation in reflected direction, the following is considered:

- To observe change of reflection for a wide angle, we need to make image sensing with a wide span of angle.
- Unlike a test on a small sample, observation of reflectance in 3-dimensional space requires object structure information.

Our approach is to move camera sensors in an active fashion and to obtain as many images as possible. With known sensor positions, we use a reconstruction algorithm similar to the ones for computerized tomography which allows us to obtain object structure according to the multiple reflection model [7]. We use an ART (Algebraic Reconstruction Technique) type algorithm modified for Lambertian optical model. Figure 4 shows the camera control scheme for image sensing. In Figure 4 (a) the camera with orthographic projection is rotated with respect to a point in the object region. The span of angle should be made as wide as possible and the incremental angle should be kept constant. A perspective camera can also be used with linear motion as shown in Figure 4 (b). The views can be rearranged for the configuration as in Figure 4 (a).

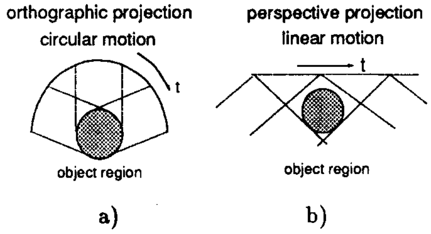


Figure 4: Camera control

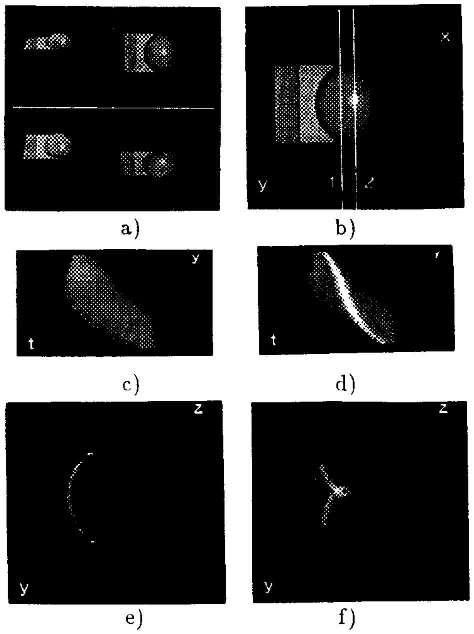
An initial experimental result is presented in Figure 5. Figure 5 (a) shows 4 out of 30 images obtained for 170° of angular span, and Figure 5 (c) and (d) show the collection of data from the 30 different views for the cross-sectional planes 1 and 2 shown in Figure 5 (b), respectively. The reconstructed surface structure from the 30 images at the cross-sectional planes 1 and 2 is shown in Figure 5 (e) and (f), respectively.

Since the reconstruction algorithm assumes the Lambertian property of reflection, only the Lambertian reflection represents real surfaces in the reconstructed space of depth. In Figure 5 (e) and (f), the thin layers represent the real surfaces represented by Lambertian reflection. On the other hand, the shape of the specularity appears differently from that of the Lambertian reflections as shown in Figure 5(c). The appearance of the specularity is as predicted by the specular reflection model, and the shape is determined by illumination size and direction, surface shape and roughness. This property can be used for identification of reflectance types.

The reconstructed values of the Lambertian component are not correct since the reconstruction algorithm is not adjusted for the opaqueness.

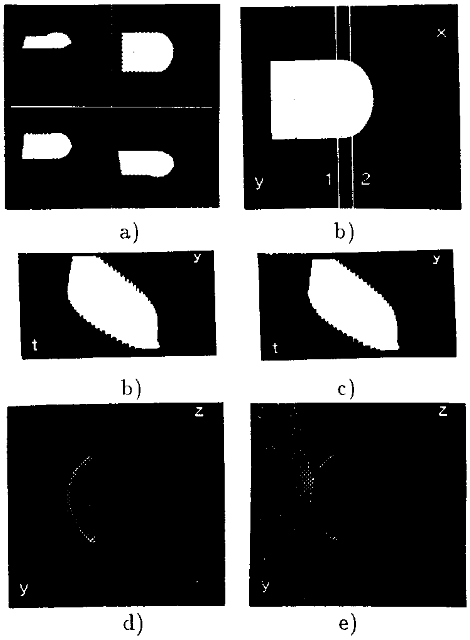
5 Determination of Reflectance Type

Although the reconstructed structures in Figure 5 are indicative of different reflectance types, it is not easy to identify the reflectance type of each point algorithmically. To identify reflectance types systematically, we use a special technique. The specular structure in the reconstructed space does not represent real surface since it results from the variation of non-Lambertian reflectance on the object. Therefore we can nullify the existence of specular structure by nullifying the variation of reflectance in the image observation. For our current algorithm, we assume that the background is dark, and we artificially assign uniform reflectance values on the object region. We call the technique *white painting*.



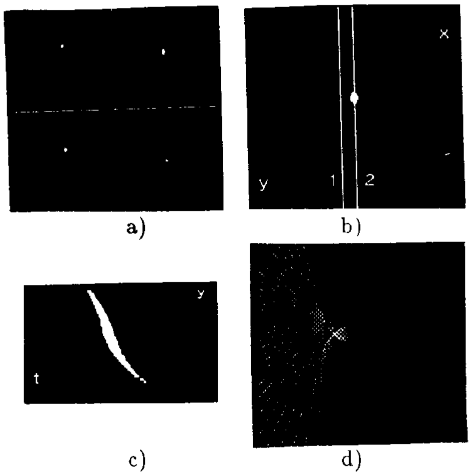
a) b) c) d) e) f)

Figure 5: Structure reconstruction



a) b) b) c) d) e)

Figure 6: Structure reconstruction using *white painting*



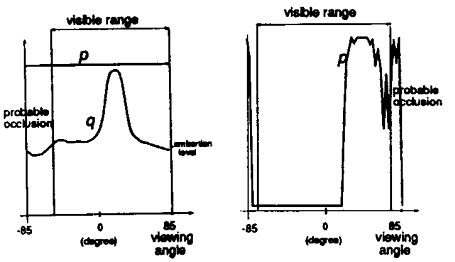
a) b) c) d)

Figure 7: Structure reconstruction of a black object

Figure 6 (a), (b), (c) and (d) show the same data as Figure 5 (a), (b), (c) and (d) except for the *white painting*. The reconstructed surface structure at the cross-sectional planes 1 and 2 is shown in Figure 6 (e) and (f), respectively. In the reconstruction, the Lambertian opaqueness is considered and compensated for with a modified ART algorithm. With *white painting*, we can see that the specularity is nullified, and the structure is only Lambertian. In order to confirm the reflectance type, we can check the Lambertian consistency for all the points in the reconstructed structure. For a point in Figure 6 (f), the observed values in corresponding viewing directions are plotted in Figure 8 (a). The flat curve p for the values after *white painting* confirms the Lambertian property. From the curve q before *white painting*, we can determine the Lambertian intensity which is the lowest value in the curve since specularities increase the intensity.

There are exceptions for this Lambertian reconstruction with *white painting*. When any Lambertian components are not observable with black dielectrics and metals, only observable reflections are specular. Figure 7 (a) shows 4 out of 30 images of a black dielectric object, and Figure 7 (c) shows the collection of data for the cross-sectional plane 2 shown in Figure 7 (b), respectively. The reconstructed surface structure at the cross-sectional plane 2 is shown in Figure 7 (d).

In order to determine the reflectance type, we check the Lambertian consistency, the observed values with corresponding views are plotted in



a) b)

Figure 8: Observed gray level values

Figure 8 (b) for a point in Figure 7 (d). With the non-flat curve p, we can easily see that it is not Lambertian.

6 Discussion

Many images with different views for wide span of observation angle enable us not only to determine reflectance types but also to reconstruct object structure. Our algorithm as it is presented in this paper assumes black background. When the background is not black, we can selectively *white-paint* the object by depth. The limitation of our algorithm is that it may not detect sharp specularities at highly curved object edges. On the other hand, those sharp specularities are well detected by other cues such as color or by simply detecting high spatial gradients. In order to overcome the limitations of each algorithm and to increase the level of confidence in reflectance analysis, we may use multiple cues such as color and multiple views in an integrated manner.

The richness of information from many images invites many different ways of interpretation. We are currently developing several algorithms which can potentially analyze multiple reflections from multiple layers of transparent materials.

7 Conclusion

We propose an algorithm for detection and separation of specularity from Lambertian reflectance using multiple images from different viewpoints. Known positions of image sensors for many images enable us to use a surface reconstruction algorithm similar to the ones used in computerized tomography to obtain object structure as well as to determine multiple reflection components regardless of material type. The identification of reflectance types is based on the different perceptual structure from specular and Lambertian reflections. Experimental results agree well with our model for perception of structure from multiple reflectance components.

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