

15—4 From Surface Roughness to Surface Displacements

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Abstract

This paper presents an extension to a measurement system to capture *bidirectional reflectance distribution function* (BRDF) values and texture maps out of images. The extension will enable the measurement of reflection effects due to surface roughness and additionally extracts a map representing local surface displacements. Different lighting conditions were used to discriminate between surface roughness and bump mapping which both result in variations of gathered reflected intensity. Experimental results will show the potential of the measurement system to capture complex reflectance characteristics, texture as well as bump maps from a set of few images. Local geometric deformations of the samples are therefore not restricted to a microscopic scale and samples with much coarser variations in surface geometry can be captured.

The resulting material description has an important impact on computer graphics applications targeted on photorealism. Using recent graphics accelerators which can handle per-pixel lighting and bump mapping even photorealistic realtime renderings are feasible.

1 Introduction

In the past few years one of the most challenging problems in digital image synthesis and especially photorealistic lighting simulation is the exact measurement of surface properties. Recent image-based measurement systems for measuring BRDF values were developed where some of them reconstruct reflectance model parameters only ([11], [3]), others additionally extract a texture map out of the gathered images ([1], [8]). Inspired by the idea of photometric stereo the third group of systems deal with the measurement of bump and reflection maps out of images utilizing a simple reflectance model ([7], [2]).

Typically in computer graphics surface properties consist of three components to ensure visual quality and to limit rendering complexity. These

components are a more or less complex reflectance model with its particular parameters, a texture description and a bump map for local surface displacements. The motivation to use texture and bump mapping also reflects new features of current graphics hardware for interactive applications. As well as in high-quality lighting simulations bump mapping as a component of a material description can increase the visual quality of the resulting digital image. Traditionally in computer graphics a two-dimensional array (bump map) is used to store local variations of the surface normal instead of geometric deformations. This is motivated by the efficient integration of surface normal perturbations in rendering algorithms and prevents the explicit modeling of local surface displacements by small faces.

2 Capturing Local Surface Orientations

One obvious way to capture surface normals would be to reconstruct the surface geometry and calculate the normals afterwards. Since only a few modifications to an existing system should allow to capture bump maps we concentrate on image-based concepts.

In [1] bidirectional texture functions are extracted from multiple-images. Variations in reflected intensity through surface deformations are stored implicitly in BTF's and not as a separate bump map. Suen and Healey [10] reuse these results for additional investigations on the dimensionality of the texture to establish a more compact representation. Rushmeier et.al. [7] and Epstein [2] adapt the idea of shape from lighting variations first introduced as photometric stereo in [12]. Capturing multiple images from a fixed camera position and different light source positions enables us to reconstruct the surface normals. For one pixel the set of Equations 1 can then be formulated where \mathbf{E} are the image irradiances, ρ is the reflection function, the matrix L includes all light source positions, and \mathbf{n} is the wanted surface normal.

$$\mathbf{E} = \rho L \mathbf{n} \quad (1)$$

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For diffuse surfaces the reflection function is simple a constant and referred as albedo ρ . By using three light source positions the surface normal can then be calculated by reforming Equation 1.

$$\mathbf{n} = \frac{L^{-1}\mathbf{E}}{\|L^{-1}\mathbf{E}\|} \quad (2)$$

It is obvious that only light source combinations can be used where the resulting matrix L is invertible. The known limitations of that method are due to shadowing effects and highlighting from specularity of the surface. Different methods were developed to eliminate shadowing and highlighting effects. Epstein et.al. [2] apply histogram inspections to overcome the limitations and in [7] three of five fixed light source positions are chosen for each pixel which deliver the intermediate image intensities. In detail they discard the lowest and highest pixel value and use the remaining three values for the basic photometric stereo algorithm. All combinations (three of five) of light sources and the corresponding inverse of the matrix L are precomputed for efficiency.

Although we focus on materials with directional diffuse characteristics the geometric configuration fits perfect to our measurement system and therefore we adapt the idea of shape from lighting variations. The next chapter will give a brief overview of our basic measurement method and a detailed description of the bump map capture extension.

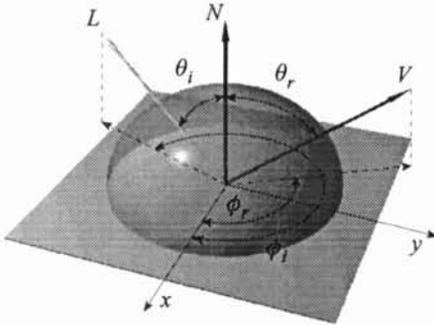


Figure 1: BRDF input variables.

3 A Measurement System to Capture Real-World Surfaces

Different image-based BRDF measurement systems were developed to capture BRDF values, model parameters, and texture (i.e. [11], [4]). The method presented in [8] additionally delivers the shape of the material under investigation using a range finder, a robotic arm and a CCD camera. Our method uses a simpler structure with a standard CCD camera and

light source but do not capture the shape of the samples. The three main steps of the algorithm are the BRDF reconstruction and model fitting, the texture analysis, and the separation of texture and bump maps.

3.1 BRDF Reconstruction

In Section 2 we treat the reflectance function simply as a factor named albedo. More general the BRDF ($f_r, [\text{sr}^{-1}]$) is the quotient of the reflected radiance to the incident irradiance and depends on lighting and viewing direction.

$$f_r(\theta_r, \phi_r, \theta_i, \phi_i) = \frac{dL_r(\theta_r, \phi_r, \theta_i, \phi_i)}{dE_i(\theta_i, \phi_i)} \quad (3)$$

$$f_{r, diffuse} = \frac{\rho_{diffuse}}{\pi} \quad (4)$$

The geometric considerations of the variables are shown in Figure 1. For simplicity we do not care about the wavelength dependence of the BRDF but mention it to be complete. Knowing the reflected radiances from the captured image we calculate the BRDF values by exploiting the symmetry of our structure and the known reflectance properties of our reference material.

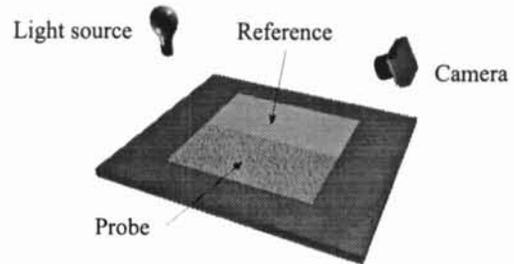


Figure 2: Structure of the measurement system.

Afterwards a parametric reflectance model will be fitted to the gathered data. One widely used model is the Ward microfacet model for isotropic and anisotropic reflection.

$$f_{r, Ward} = \frac{\rho_d}{\pi} + \frac{\rho_s}{\sqrt{\cos \theta_i \cos \theta_r}} \cdot K \quad (5)$$

K for isotropic reflectance:

$$K = \frac{\exp[-\tan^2 \delta / \alpha^2]}{4\pi\alpha^2} \quad (6)$$

A detailed explanation of the BRDF reconstruction and model fitting process can be found in [3].

3.2 Highlight Eliminated Textures

Digitized images are widely used to texture virtual objects. Unfortunately the gathered intensity values include texture information as well as highlighting components due to specularly of the surface. In [6] the specular components are eliminated by using sequences of images with different viewpoints.

Our method to separate texture information from highlights is much simpler assuming that the surface under investigation is planar and specularity is a global material property which does not change over the whole surface. Planar means in this context that the surface is flat beside a roughness at a microscopic scale. Reusing Equation 3 the specular term can be calculated for each pixel and subtracted from the corresponding BRDF value. The remaining diffuse reflectance term (ρ_d/π) for all pixels will now represent the texture of the surface [5].

Variations of measured BRDF values from parameter model estimation can have two reasons. One will be the change of reflectance properties as mentioned above (texture) the other possibility is the local displacement of the surface which results also in a change of the reflected intensity. We now describe our approach to separate these two effects.

3.3 Separating Texture and Local Surface Displacements

For surfaces with more complex reflection characteristics the photometric stereo method cannot be used directly. Nevertheless lighting variations will assist to detect surface patches where the local surface orientation differs from the unique surface normal.

At first we take a series of images with fixed camera and different light source position and reconstruct all BRDF values. The next step is to estimate the texture (ρ_d) for all pixels in each image as explained in Section 3.2. For pixels where the corresponding surface normal is not perturbed the estimated texture values in each image must be the same. At all other locations the specular term in the reflection model has some error due to the incorrect surface normal. Therefore the texture estimate will have different values for different light source positions. Now we mark all pixels which have variations in the estimated texture components as potential candidates for a local surface displacement. For all those pixels we vary the surface normal and again estimate the ρ_d for each image. The final surface normal will be the one with the lowest corresponding variance of ρ_d . This delivers a solution for the local surface normal and additionally the estimated texture at those previously selected candidates. The

variation of surface normals is carried out by a simulated annealing technique ([9]).

4 Experimental Results

To demonstrate the capability of our method an object with moderate directional diffuse reflectance, a strong texture, and a geometric deformation was selected. Five different light source positions and one fixed camera location were used to capture the input images (see Figure 3). The variances for the estimated diffuse reflectance coefficients after the first parameter model fitting is shown in Figure 4. Areas with high variations matches areas in images where surface displacements influences the reflected intensities.

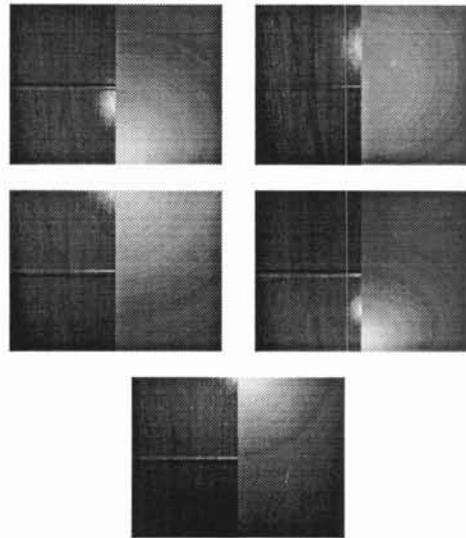


Figure 3: Captured images at a fixed camera position and five different light source positions.

In Figure 5 a comparison of the estimated texture map with and without consideration of surface deformation is shown. Artifacts from highlighting and surface deformation are almost completely eliminated in the resulting texture shown on the right side.

5 Conclusion and Future Work

We have presented an extension to an image-based measurement system which captures reflectance characteristics and texture information to additionally detect local surface deformations. These deformations are stored in bump maps which can effectively be used in modern graphics accelerators.

Although the first results are quite promising it is necessary to test our developed method with different materials. Further investigations will also include an analysis of the extracted bump map to find

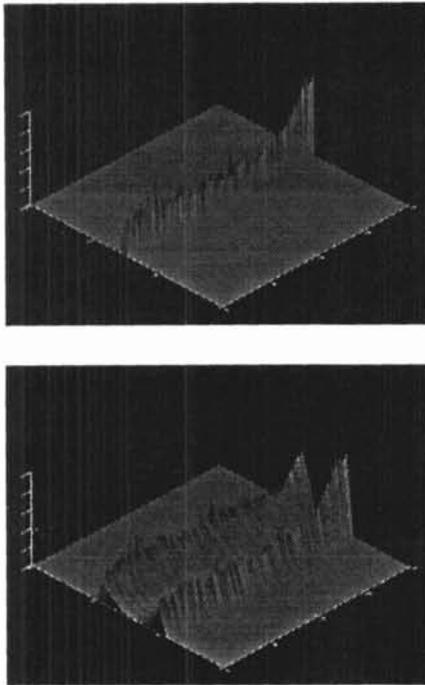
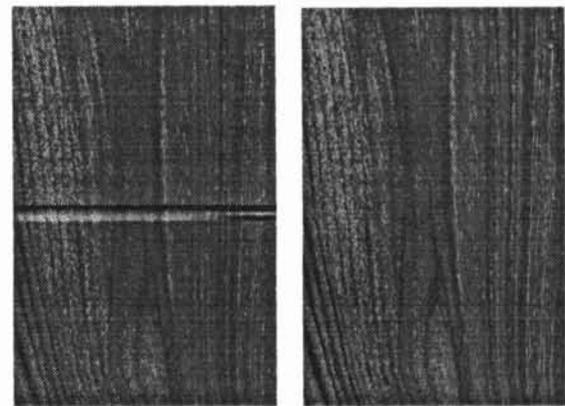


Figure 4: Variances of estimated ρ_d (source images in Figure 3). The lower picture shows a zoomed view

a parametric description. This will allow to apply the captured bump maps on virtual objects with unlimited spatial extend.

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(a) artifacts due to incorrect surface normal handling

(b) correct reconstructed texture (no visual artifacts)

Figure 5: Reconstructed texture maps with and without consideration of local surface displacements (bumps) using the same input image.

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