Texture Mapping Based on Coefficient Map and Basic Texture Map

Huijian Han
School of Computer Science & Technology, ShanDong Economic University, Jinan ,China
Shandong Prov. Key Lab of Digital Media Technology, Jinan ,China
Email: hhj@sdie.edu.cn

Hengwu Li
School of Computer Science & Technology, ShanDong Economic University, Jinan ,China
Email: smxlhw@sina.com

Abstract—Texture mapping may give the impression of geometric details in a model using an image. But texture always was captured under special light condition. If the lighting in virtual environment is different from the texture image, the result of rendering will be incorrect and unrealistic. This paper proposes an image-based method that requires basic texture map and coefficient maps to interpolate light effective. This method uses a quadratic multinomial to fit the reflection model. The coefficients of quadratic multinomial will be gained from BTFs and are stored as coefficient maps. A picture is taken under well-proportioned environment light as a basic texture map, which the chromaticity is saved. The method can reconstruct the surface color under varying lighting conditions and represent the variation in surface color for each texel independently. Coefficient map and basic texture map make texture mapping become more realistic, simple and convenient.

Index Terms—texture mapping, coefficient map, basic texture map, image-based

I. INTRODUCTION

In the reality scene, there are three basic structures in the geometry, namely macrostructure, mesostructure and microstructure. The macrostructure with the certain geometry shape can be seen by the eyes, such as building, furniture shape etc. Mesostructure with quite small geometry shape still can be seen, for instance orange’s skin. Microstructure is the micro unit of surface can’t be seen. The Microstructure affects optical quality such as light scattering. The mesostructure causes visual effect [1] like roughness, self-shadows, occlusions, inter-reflection and subsurface scattering etc., which is an important factor that we get the realistic object surface with rich detail [2]. Mesostructures are typically rendered using techniques such as bump mapping [3], horizon mapping [4] or displacement mapping [5]. Mesostructure and microstructure decide the optical quality and the detail visual quality of object surface.

Using traditional texture, for example a realistic image, may realistically increase the model’s geometry detail by mapping texture to the surface of object. However, because the texture is generally get by taking photographs under some special viewpoint position and specific lighting condition. When this texture is mapped to the 3-D object surface, the lighting condition in the virtual scene is not considered. If the lighting in the virtual environment is consistent with the lighting which the texture was captured under, the reality is the most strong. Contrarily, the result of rendering will appear incorrect and unrealistic. Bump mapping provides basic shading, which perturbs mesh normals to match those of the fine geometric detail, but not shadowing, occlusion, and silhouettes. Introducing variations in the surface normals causes the lighting method to render the surface as though it had local surface variations instead of just a smooth surface. Bump maps can be either hand modeled or, more typically, calculated procedurally. But it is still difficult to create a bump map base on real pictures.

This paper offers an image-based method for representing various lighting effect, which is suitable for the diffuse and specular reflection object. The pictures are captured under fixed viewpoint and under kinds of illuminations condition. We choose a polynomial model to describe the variation of each texel’s luminance. The polynomial coefficients can be stored as maps for basic texture. The basic texture and its coefficients maps can be mapped to the object simultaneously. This method can reconstruct the texture’s luminance and color under varying lighting conditions.

II. RELATED WORK

With very simple geometries, texture and bump mapping yield good results for simple materials, but for more complex materials we need the ability to change the appearance for varying light and viewing conditions. Early approaches simulated a single BRDF for the whole material [6]. Kautz and McCool [7] approximated the BRDF by two functions, whose results are stored in textures and were combined by the graphics hardware. These methods, which improved by [8] [9] and [10], lit
by prefiltered environment maps, but their models are currently not capable for real-time rendering of BTFs. For fixed viewpoint the polynomial texture map by Malzbender et al. [11] can be suitable for varying light conditions. Huijian Han et al. [12] proved through experiments that quadratic polynomial approximation can simulate diffuse reflection and specular reflection effects.

A. BRDFs

BRDFs were introduced by Nicodemus [13]. These functions describe the reflection distribution at a surface point depending on incoming and outgoing light directions. BRDFs overcome the limitations of geometry coupling, fixed lighting and viewing directions. Early results approximated a single BRDF by a Ward [14] or Lafortune [15] model. BRDFs are five variables function $f(\theta_i, \Phi_i, \theta_e, \Phi_e, \lambda)$. The BRDF is the ratio of the reflected intensity in the exitant direction to the incident energy per unit area along the incident direction. It does contain a dependence on wavelength $\lambda$, but in practice this is often approximated by independent BRDFs per color channel (RGB). They completely describe reflected light distribution of one point in opaque surface. Specifically, its value is the survey ratio of reflecting illumination intensity ($dI$) and incoming illumination intensity ($dE$), which depends on the assigned direction, the specific wave length $\lambda$, unit solid angle $d\omega$. Thereinafter, all the quantities that relate to incidence are expressed by the subscript ‘i’, and all the quantities that relate to outgoing are expressed by the subscript ‘e’, namely:

$$f_e(\theta_i, \phi_i, \theta_e, \phi_e, \lambda) = \frac{dI(\theta_i, \phi_i)}{dE(\theta_i, \phi_i)}$$

In the above formula, $\theta_i, \Phi_i, \theta_e$ and $\Phi_e$ respectively are azimuth angle of incoming light and outgoing light, in the figure 1:

![Figure 1. The azimuth schematic drawing of surveying BRDF](Image)

For the reflection distribution of opaque surface, surveying the BRDFs is needed. Although the BRDFs can accurately describe the reflection characteristic of an object, in general measure is extremely complex. The theoretical calculation of the BRDFs needs to determine optics parameters of the roughness surface and roughness statistics parameters, but accurately obtaining the above parameters is difficult in practical application. At present there have been a large number of techniques developed to accurately and compactly represent the 4D BRDF, for example, spherical harmonics [16], [17] etc., physically based analytic models [18], [19], and empirical models [20], [21].

B. BTFs

BTFs were introduced by Dana et al. [22]. A planar surface sample is lit by a directional light source and photographed from different directions. In the image captured the color of every pixel is caused by different directions of light source and different angle of capturing. Thus the resulting images are a function of viewing and illumination direction. All appearance, registering the different images of the BTF the data can be considered as a 6 variables reflectance field:

$$I = I(x, y, \theta_i, \phi_i, \theta_o, \phi_o)$$

where $(x, y)$ is the position of pixel in the created image, and $\theta_i, \Phi_i, \theta_o$ and $\Phi_o$ respectively are azimuth angle of incoming light and outgoing light respectively. The measurement is done in RGB space, wavelength changes and time dependent effects like fluorescence are ignored. BTFs were possible to render materials under varying light and view conditions. But due to the big amount of data in BTFs and the computational complexity of the function, it is needed to compress the data in specific models to achieve interactive rate. There are only few real-time rendering algorithms exist [23],[24]. Kautz and Seidel [7] proposed a factorization of the texel wise BRDF in two dimensional functions whose coefficients are stored in textures to be computed with hardware supported operations and dependent texture lookups.

The BTF does not actually store the ratio of extant to incident energy like the BRDF. Instead, the BTF captures the pre-integrated lighting condition for a particular light source. A BTF can be regarded as 2D-texture where each pixel $(x, y)$ is not a color value, but approximately a BRDF $(\theta_o, \phi_o, \theta_i, \phi_i)$. In a sampled BTF, one has a number of images for each light and view direction. These stacked images form the BTF sample and give a high dimensional vector for each pixel. Numerous photographs will be required to adequately sample this space. In their pioneering work, Dana et al. [25] measured 61 samples of real-world surfaces and made them publicly available in the CUREt26 database. Unfortunately, their data is not spatially registered. A drawback of the CUREt database is that it contains some graphical errors, caused by frame-grabber artifacts or reflections of the robot sample holder plate visible in the raw data. Another problem with BTF samples is that they are taken from real world samples with limited sizes and that large sample need huge amounts of memory, Simple tiling of the measured samples usually leads to visible borders. So BTFs synthesis algorithms studying are important direction.

III. TEXTURE LUMINANCE FITTING

A. Fitting BTFs data

According to the thinking of Malzbender et al [11], in order to simplify the BTF model, this paper only considers the situation of fixed viewpoint and keeps the two dimensions in extant direction constant, namely the
reflection field of BTFs is \( I = I(x, y, \theta_i, \phi) \). Under the special illumination circumstance, now one picture is a space sampling of two-dimensional, and to each point \((x, y)\), the change of \( I \) is only relevant with \((\theta_i, \phi)\). The principle of gaining BTFs sample of fixed viewpoint is described as figure 2.

![Figure 2. Schematic drawing for sampling BTFs with fixed viewpoint](image)

Phong developed a popular illumination model. It is

\[
I = I_0 k_a + I_p (k_d (\overrightarrow{N} \cdot \overrightarrow{L}) + k_s (\overrightarrow{N} \cdot \overrightarrow{H}))
\]

(1)

where: \( \overrightarrow{H} = (\overrightarrow{L} + \overrightarrow{V}) / | \overrightarrow{L} + \overrightarrow{V} | \)

If without considering ambient light, when \( k_0 = 0 \), Phong’s model becomes Lambert’s law, namely:

\[
I = I_p k_d (\overrightarrow{N} \cdot \overrightarrow{L})
\]

(2)

When \( k_d = 0 \), Phong’s model becomes specular reflection, namely:

\[
I = k_s (\overrightarrow{N} \cdot \overrightarrow{H})^n
\]

(3)

where:

\[
\overrightarrow{N} = a_i + a_j x + a_k y
\]

\[
\overrightarrow{L} = b_x + b_y y + b_z z
\]

\[
\overrightarrow{N} \cdot \overrightarrow{L} = a_x b_x + a_y b_y + a_z b_z
\]

\[
= a_x b_x + a_y b_y + a_z (1 - b_x^2 - b_y^2)
\]

Let: \( f_d = I(I_p k_d) \) and according to the formula (2), then:

\[
f_d = a_x b_x + a_y b_y + a_z (L - b_x^2 - b_y^2)
\]

(4)

\[
f_d = (-a_x^2 - a_y^2)(1/f_0) b_x^2 + (-a_x^2 - a_y^2)(1/f_0) b_y^2 + (-2a_x b_x)(1/f_0) b_x + (2a_y b_y)(1/f_0) b_y
\]

Let:

\[
q_0 = -a_x^2 - a_y^2, \quad q_1 = -a_x^2 - a_y^2
\]

\[
q_2 = 2a_x, \quad q_3 = 2a_x
\]

In fact, coefficients \( k_0 q_0, k_d q_5 \) reflects the each sample point’s reflectance characteristic in the surface of object. \( k_0 q_0, k_d q_5 \) are called as diffuse reflectance coefficients in this paper.

Without loss of generality, the varying of \( I/f_d \) in the right of formula (4) is ignored, namely \( I/f \) may be regarded as a constant, because \( k_d, b_x, b_y, a_x, a_y, a_z \leq 1 \) and \( k_1 * b_x \) and \( k_2 * b_y \) are main factors which cause changing of \( f(x, y) \). Then let \( q_0 = q_0 * I/f_d, q_1 = q_1 * I/f_d, q_2 = q_2 * I/f_d, q_5 = q_5 * I/f_d \). Then Eq.(4) can be rewritten as

\[
f_d = q_0 b_x^2 + q_1 b_y^2 + q_2 b_x b_y + q_3 b_x + q_4 b_y + q_5
\]

(5)

Let: \( f_d = I(I_p * k_d) \), we may similar to fitting Eq.(3) by following Eq.(6) [17].

\[
f_s = p_0 b_x^2 + p_1 b_y^2 + p_2 b_x b_y + p_3 b_x + p_4 b_y + p_5
\]

(6)

Therefore, for objects with both specular reflection and diffuse reflection property, we can similar to fitting Eq.(1) by following Eq.(7). Let \( f(x, y) = I/I_p \). Without considering ambient light.

\[
f(x, y) = k_0 b_x^2 + k_1 b_y^2 + k_2 b_x b_y + k_3 b_x + k_4 b_y + k_5
\]

(7)

As shown in figure 2, \( N+1 \) photographs are taken under fixed viewpoint and varying lighting conditions. Each photograph corresponds with a light source position. Then every the same position texel in texture space has \( N+1 \) values of brightness and every value corresponds with a known direction of ray. It can be seen that \( I \) and \( b_x, b_y \) can be measured. The value of \( I \) is expressed from 0 to 255, so realistic brightness of light source \( I_p \) is regarded as 255. \( f(x, y) \) can be computed using luminance of gradation charts. In view of \( N+1 \) samples of each texel, the equation with six unknown coefficients of \( k_0-k_5 \) is given by formula (7). The fitting algorithm uses singular value decomposition (SVD) to solve the following system of equations, which leads to the minimal least squares error. The SVD can be computed once and be applied per texel. Given \( N+1 \) images, for each texel coordinate, we get \( N+1 \) equations and compute the best fit in \( f \) to solve the following system of equations for \( k_0-k_5 \).

\[
\begin{pmatrix}
    b_{x0}^2 & b_{y0}^2 & b_{x0} b_{y0} & b_{x0} & b_{y0} & 1 \\
    b_{x1}^2 & b_{y1}^2 & b_{x1} b_{y1} & b_{x1} & b_{y1} & 1 \\
    \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
    b_{xN}^2 & b_{yN}^2 & b_{xN} b_{yN} & b_{xN} & b_{yN} & 1
\end{pmatrix}
\begin{pmatrix}
    k_0 \\
    k_1 \\
    \vdots \\
    k_N
\end{pmatrix}
= \begin{pmatrix}
    f_0 \\
    f_1 \\
    \vdots \\
    f_N
\end{pmatrix}
\]

(8)

\( f_{0}, \ldots, f_{N} \) is a rate of energy of outgoing light to incoming light in each texel area, which is measured per texel of varying light directions. \( b_{x0}, b_{y0} \) is the projection for the
first light-direction to the local texture coordinate system, \( b_{x}, b_{y} \) the projection of the second and so on.

### B. Basic Texture Map and Polynomial Coefficient Map

In real world, the color of object not only depends on the material itself but also relates to the light source, the color of environment etc. The influence factors are quite complex. When the object is only irradiated by white light, the color of object is decided by reflection characteristic of itself. In general, no matter where the ray comes from, the chromaticity of a particular texel is fairly constant under varying light source, namely the proportion among \( R, G \) and \( B \) is invariable, and only varying value is the emerge of reflex light (Luminance). In computer, the every value of RGB expresses luminance of each color channel. Under varying light source every component’s value of RGB synchronously changes. We can assume, that the color will be constant under varying light directions and fit only the BRDF(\( f(x,y) \))’s luminance value and modulate base-color with it. As shown in figure 1, if a picture is taken under well-proportioned environment light, we can get the color of sample point on eyeable surface of object and at the same time the chromaticity is saved. Where, the color \( R_{p}G_{p}B_{p} \) that obtained under well-proportioned environment light are named base-color in this paper. The base-color \( R_{p}G_{p}B_{p} \) of all texels constitute basic texture map. The base-color \( R_{p}G_{p}B_{p} \) are described as Eq.(9).

\[
\begin{align*}
R_{B} &= \begin{pmatrix} R_p \\ G_p \\ B_p \end{pmatrix} \ast k_u + \max \left\{ \begin{pmatrix} R_p \\ G_p \\ B_p \end{pmatrix} k_d (\vec{N} \cdot \vec{L}) \right\} \\
G_{B} &= \begin{pmatrix} R_p \\ G_p \\ B_p \end{pmatrix} \\
B_{B} &= \begin{pmatrix} R_p \\ G_p \\ B_p \end{pmatrix}
\end{align*}
\]

(9)

The coefficients of system of equations (8) \( k_{c-k_s} \) will be gained from BTFs and are stored for per texel. To facilitate the storage, the maximum and minimum values of \( \{k_{c-k_s}\} \) are between -2 and 5. The coefficients are mapped to the numerical range 0-255. Figure 4 describes six coefficient maps that every coefficient is stored in a map. Figure 6 describes three combinations of coefficients that every three coefficients are stored in a map. Six coefficients can be stored into two maps. Experiment is to choose the first combination. Figure 5 is basic texture map that is taken under well-proportioned environment light and the chromaticity is saved. Figure 7 describes comparing between the actual results and this paper’s simulation result of slippery object under four different light source position.

### C. Applications of Maps

Consequently, although approximate, this representation is compact and allows fast color reconstruction during rendering.

**Figure 3.** Schematic map of texture mapping with basic texture map and polynomial coefficient map

**Figure 3** describes the principle of the application of texture map and coefficient maps. In the computer simulation, may designate \( R_{p}G_{p}B_{p} = 255 \). If the picture is captured in the real environment, \( R_{p}G_{p}B_{p} \) are basic texture picture’s luminance under well-proportioned environment light. Basic texture map applying in luminance-model means that it re-computes the color value (\( R(x,y),G(x,y),B(x,y) \)) of current texel under arbitrary incident ray. See formula (10).

\[
\begin{align*}
R(x,y) &= k \ast R_{p} \ast f(x,y) \\
G(x,y) &= k \ast G_{p} \ast f(x,y) \\
B(x,y) &= k \ast B_{p} \ast f(x,y)
\end{align*}
\]

(10)

\( k \) is a coefficient to adjust brightness of texture image. It is an empirical value that enables recreating more real texture within the range of possibilities. In general, \( k = 1 \). In Eq.(10), \( R_{p}G_{p}B_{p} \) from the basic texture map, \( f(x,y) \) from the coefficient maps.

**IV. EXPERIMENTS AND CONCLUSIONS**

**A. Experiments**

Choose to use computer simulation experiments of slippery object. The maximum and minimum values of \( \{k_{c-k_s}\} \) are between -2 and 5. The coefficients are mapped to the numerical range 0-255. Figure 4 describes six coefficient maps that every coefficient is stored in a map. Figure 6 describes three combinations of coefficients that every three coefficients are stored in a map. Six coefficients can be stored into two maps. Experiment is to choose the first combination. Figure 5 is basic texture map that is taken under well-proportioned environment light and the chromaticity is saved. Figure 7 describes comparing between the actual results and this paper’s simulation result of slippery object under four different light source position.

**B. Conclusions**

This paper proposes an image-based method that requires basic texture map and coefficient maps to interpolate light effective. The input data required is a set of images (BTFs) under different light direction. Each one under illumination from a different known direction is captured from the same view point. This method uses a quadratic multinomial to fit the reflection model. The coefficients of quadratic multinomial will be gained from BTFs and are stored for per texel as coefficient maps. A picture is taken under well-proportioned environment light as a basic texture map, which gets the color of sample point on eyeable surface of object and the chromaticity is saved. The method can reconstruct the surface color under varying lighting conditions and represent the variation in surface color for each texel independently. Application of coefficient map and basic texture map, texture mapping has become simple, convenient. Although approximate, this representation is compact and allows fast color reconstruction during rendering.
The model is simple but capable of approximating diffuse materials and highly specular materials. As we are using images to fit the model, effects like self-shadowing, sub-surface scattering and inter-reflections will be preserved as the reflection characteristics of the material. One main implementation of this method is to be used to approximately compute the luminance of each texel, keeping the chromaticity constant. The method can be used in texture mapping, which texture may properly reproduce the variational effects under the different virtual light condition.

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Huijian Han, Male, was born in HeZe city, China, in December 19, 1971. In 2000, Han is a master majoring in Computer Software Theory and Techniques of Shandong University, China, and now as Computer Applied Technique Ph. D. candidate in Shandong University. Han’s major field of study is texture mapping of CG. He is a professor, master tutor in School of Computer Science & Technology of ShanDong Economic University and Shandong Prov. Key Lab of Digital Media Technology, in Jinan city, China. He participated in the work in 1992 and has long been engaged in computer technology in teaching and research work. He has published more than 30 papers in academic journals at home and abroad and participated in the preparation of two books. For example: Computer Graphics (Beijing, China: Science Press,2005); Concise Guide to Computer Graphics
(Beijing, China, Higher Education Press, 2007); Determining Knots by Minimizing Energy (Beijing, China, Journal of Computer Science and Technology, 2006). His current research interests include CG & CAGD, computer simulation and digital media techniques.

Prof. Han is a member of Chinese Association for System Simulation, Computer Society of Shandong Province, and Academic Committee of Shandong Prov. Key Lab of Digital Media Technology. Prof. Han received third prize of Shandong Province Natural Science Award in 2005, received first prize of Science and Technology Progress Award of People's Republic of China Ministry of Education in 2007 and received Outstanding Contribution Award from the Shandong Provincial Science and Technology Association in 2008.

Hengwu Li, Male, was born in Jiaonan city, China, in 1969, Ph. D. in Computer Software Theory and Techniques of Shandong University, China, in 2008. Li’s major field of study is analysis and design of algorithm.

He is an Associate Professor in School of Computer Science & Technology of ShanDong Economic University and Shandong Prov. He participated in the work in 1991 and has long been engaged in computer technology in teaching and research work. He has published more than 20 papers in academic journals at home and abroad. For example: Prediction for RNA Planar Pseudoknots (Journal of Progress in natural science, 2007); New Algorithm for Predicting Ribonucleic Acid Secondary Structure Including Pseudoknots (Journal of tongji university, 2004); A Polynomial Algorithm to Compute the Minimum Degree Spanning Trees of Directed Acyclic Graphs with Applications to the Broadcast Problem. (Journal of Discrete mathematics, 2008). His current research interests include analysis and design of algorithm, biological computation and electronic commerce.

Figure 4. Single coefficient map

Figure 5. Basic texture map
Reconstructing result of slippery object applying basic texture map and coefficient maps.

Figure 6. Several combine of coefficients map

Reconstructing result of slippery object applying basic texture map and coefficient maps.

Actual results of slippery object in Phong’s model (n=12)

Figure 7. Comparing between the Actual results and Reconstructing result of slippery object under four different light source position. (ka /kd / ks is 0.0/0.4/0.6; n=12)