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Subsurface scattering using splat-based diffusion in point-based rendering

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Abstract Point-based graphics has gained much attention as an alternative to polygon-based approaches because of its simplicity and flexibility. However, current point-based techniques do not provide a sufficient rendering quality for translucent materials such as human skin. In this paper, we propose a point-based framework with subsurface scattering of light, which is important to create the soft and semi-translucent appearance of human skin. To accurately simulate subsurface scattering in multilayered materials, we present splat-based diffusion to apply a linear combination of several Gaussian basis functions to each splat in object space. Compared to existing point-based approaches, our method offers a significantly improved visual quality in rendering human faces and provides a similar visual quality to polygon-based rendering using the texture space diffusion technique. We demonstrate the effectiveness of our approach in rendering scanned faces realistically.

Keywords subsurface scattering, point-based rendering, skin rendering, diffusion profile, sum of Gaussian

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1 Introduction

Point-based rendering is becoming an increasingly popular alternative to polygon-based rendering. Instead of rendering a triangular mesh, point-based rendering acts directly on an unstructured cloud of points. This is particularly beneficial if the model being rendered is undergoing frequent major geometric changes; complicated modifications to connectivity information are avoided. It is also effective with high-resolution models. However, many of the existing rendering techniques are unsuitable for point clouds because they are originally designed for polygons. So several researchers have made an effort to transfer techniques designed for polygon-based rendering to point-based rendering, allowing special effects to be achieved such as motion blur [1], non-photorealistic rendering [2], and transparent shading [3]. As point-based rendering becomes more popular, realistic rendering techniques for various materials have become necessary within a consistent framework for point clouds. One example is subsurface scattering, which is a realistic way of rendering translucent materials such as milk, marble, leaves, and human skin. Subsurface scattering in such materials has been extensively studied in recent years, but very few efforts have been made in point-based rendering.

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Figure 1 (Left) A set of surface splats; (Middle) point-based rendering with bidirectional reflectance distribution function; (Right) point-based rendering with bidirectional surface scattering reflectance distribution function.

We propose a method of modeling subsurface scattering which allows the appearance of translucent materials to be modeled by point-based rendering. Our key idea is inspired by d'Eon and Luebke's technique [4] for realistic rendering of facial skin. They approximate a multipole diffusion profile [5] for multilayered materials as a linear combination of Gaussian basis functions, and we have modified this procedure to suit point-based rendering. In our framework, the effect of light diffusion is represented by a Gaussian distribution applied to the radius of a surface splat [6] and multicolored layers of increasing radius are linearly combined in object space. Given a set of surface points or splats in Figure 1(left), our point-based rendering (Right) with subsurface scattering effects produces more realistic results than the previous point-based rendering (Middle) when rendering translucent materials such as human skin.

Earlier methods of modeling subsurface scattering required several seconds or even minutes to render one scene, making real time rendering impossible [5, 7]. Various improvements have been introduced but require a great deal of pre-processing [8, 9]. This is ineffective if pre-processing has to be repeated for every scene because the model is undergoing animation or deformation. However, a recent method [4] avoids pre-processing by combining texture space diffusion with an extended translucent shadow map. This allows translucent objects with changing scenes to be rendered in real time.

We propose a splat-based diffusion technique which uses a linear combination of Gaussian basis functions, in a similar way to texture space diffusion. This allows realistic rendering without pre-processing. Moreover, because the combination of Gaussian basis functions takes place in object space, the texture distortions caused by the large ratio between distances in texture space and Euclidean space are avoided without any additional stretch correction step. We also can improve the speed by reducing the number of splats when the amplitude of the radius is large during the process of the splat-based diffusion. We will show that the presented technique can be used to realistically render human skin represented as a point cloud.

2 Previous work

2.1 Point-based rendering

Point-based rendering was introduced in 1985 by Levoy and Whitted [10], who first used the point as a rendering primitive. Subsequently, Grossman and Dally [11] suggested a method in which points are combined by multiple orthographic projections and a hierarchical z-buffer is used to decide visibility. The addition of a multiresolution approach achieved a uniform sampling density with complicated scenes. However, this method was only efficient within a limited interval of viewing distances.

Pfister et al. [12] proposed surfels, which locally approximate the surface of a model. A scene is then rendered using a hierarchical data-structure called layered depth cubes (LDC). Subsequent point-based rendering methods can be divided into image-space or object-space techniques. Surface splatting associates a normal vector and radius information with each point on a surface so as to avoid holes in the rendered image. This development has been influential, and various algorithms based on surface splatting have been developed, running in a CPU or in graphics hardware. Splat shapes range from simple image-space squares [13] or circular splats [14, 15] to elliptical splats [16].

Like most discretization approaches, point-based rendering involves an aliasing problem on the surface which is reconstructed through rendering. To solve this problem, EWA surface splatting [6] was proposed. This is a high-quality rendering technique which uses a splat with a Gaussian filter kernel to interpolate information between points. This technique has been developed in various directions. With the increasing programmability of modern GPUs many parts of the original algorithm have been delegated to the graphics hardware to improve the rendering speed. In 2004, Botsch et al. [17] introduced GPU-accelerated Phong splatting for per-pixel shading scheme similar to Phong shading. In the following year, Botsch et al. [18] produced a similar Phong shading effect by interpolating the normal vectors on the surface of a model using a deferred shading with multi render targets. Deferred shading provided a clear separation between the rasterization and the shading computation.

Several other researchers have tried to transfer techniques designed for polygon-based rendering to point-based rendering. Guan and Mueller [1] adapted motion-blur for point-based rendering. In Zakaria's thesis [2], a method to find the silhouette of a point cloud was proposed, allowing several non-photorealistic rendering effects to be achieved. Zhang and Pajarola [3] introduced a technique called deferred blending, in which several sets of point data are separately rendered on different layers and subsequently combined. This allowed the blending of materials with different properties, which was not previously feasible with point-based rendering.

2.2 Subsurface scattering

Subsurface scattering is important for photo-realistic rendering of translucent materials. Hanrahan and Krueger [19] used a Monte-Carlo simulation to develop a local reflectance model to simulate scattering in 3D models with one or more layers. In 2001, Jensen et al. [20] proposed a practical way to use the dipole model to accurately simulate the scattering process that takes places inside translucent materials. Later, Donner and Jensen [7] put forward an extended dipole model, called the multipole model, to render skin more realistically than the dipole model. This method simulates the transmission and reflection of light inside multi-layered translucent materials such as skin.

A real time skin rendering method based on recent research was announced by d'Eon and Luebke [4]. It essentially divided the arithmetic processes required for lighting into two components. The specular BRDF method is used for specular effects and an approximation of subsurface scattering is used for diffuse effects. Assuming a three-layer skin model, the specular BRDF method realistically simulates the light reflection caused by the sebum of the topmost layer. This technique, based on Weyrich's thesis [21], uses a separate roughness and reflectance intensity for the area around each point in a face model which has been captured by a scanning device. This data is used in a fast Fresnel approximation, which contributes to BRDF's Fresnel terms. Subsurface scattering is approximated by extending and combining existing techniques for texture-space diffusion [22] and translucent shadow mapping [23], so as to allow real-time handling of the diffusion of light within the skin. This approach allows realistic real-time rendering of a face model without any pre-processing.

3 Background

3.1 The splat-based representation

Point-based rendering uses splat primitives, in which each point in a point-model becomes an elliptical-shaped rendering primitive. Each splat consists of an ellipse with a central point, a radius, and a surface color, as well as a normal vector. If a group of points is composed of splats, consecutive splats $s_0 ... s_{n-1}$, which are elements of point set S, can create the surface of a 3D model. To smoothly interpolate the color of each splat, the color of $c(f_i)$ of fragment f_i is found as follows:

$$c(f_i) = \frac{\sum_i w_i(f_i) c_i}{\sum_i w_i(f_i)}. \tag{1}$$

The weight w_i applied to fragment f_i is proportional to the distance from the splat's median p_i to the fragment f_i.

Weight w_i is applied by finding a Gaussian contribution of weights in object space. The colors of the fragments accumulated in one pixel are normalized by dividing by the appropriate totals, so that splats appear to be blended together.

To prevent the weight of splats occluded by other splats being included in the accumulation, an ε-z-buffer visibility test is conducted. This is a depth test that eliminates a splat s_j which is behind and within a certain distance ε from splat s_i.

3.2 The fast approximate diffusion profile for subsurface scattering

The diffusion profile is the core concept in models of subsurface scattering. It allows realistic approximation of the diffusion of light immediately below the surface of a translucent material. For example, suppose that there is a very thin sheet of translucent material in a dark room, and then a white laser is directed perpendicularly to a single spot on this plane. The light diffuses beneath the surface and illuminates the surrounding region of the material. The diffusion profile is an index that expresses how far this diffusion spreads.

To approximate the diffusion profile accurately in real time, we use a Gaussian basis function. However, as a realistic diffusion profile cannot be achieved with a single Gaussian, we combine a number of Gaussians. If each diffusion profile is $R(r)$, and there are k Gaussian weights w_i, with dispersions v_i, then a sum of Gaussian is constructed as follows:

$$R(r) \approx \sum_{i=1}^{k} w_i G(v_i, r). \tag{2}$$

The diffusion profile of a real material can be measured by analyzing the diffusion pattern produced by a laser. A real profile must be fitted by a number of Gaussians, using error minimization. If the diffusion profile to be achieved is $R(r)$ Gaussian required can be expressed as follows:

$$\int_0^{\infty} r\left(R(r) - \sum_{i=1}^{k} w_i G(v_i, r)\right)^2 dr, \tag{3}$$

where the error between the target diffusion profile $R(r)$ and the Gaussian sum is weighted by the radial distance r.

The error of this fitting function can be expressed as follows:

$$E = \frac{\sqrt{\int_0^{\infty} r(R(r) - G_{\mathrm{sum}}(r))^2 dr}}{\sqrt{\int_0^{\infty} r(R(r))^2 dr}}. \tag{4}$$

4 Point-based rendering with subsurface scattering

We propose a new rendering framework for the realistic rendering of point-based models of multilayered translucent materials using a splat-based diffusion technique. Figure 2 shows our rendering framework which consists of typical three passes and newly added two passes.

4.1 Rendering framework

The majority of GPU-accelerated point-based rendering methods create images through a three-pass procedure: visibility-splatting pass, attribute-splatting pass, and shading pass. All these passes are performed by programmable shaders: the first two passes use the point geometry data as input, and the final pass operates on the image pixels generated by the previous two passes. In general, three passes are necessary because OpenGL, DirectX and other graphics libraries do not support elliptical splats as a rendering primitive. To find the exact depth of a 3D surface made by a set of overlapping splats, accurate depth information must be calculated in the first pass and stored in a depth buffer. The second pass

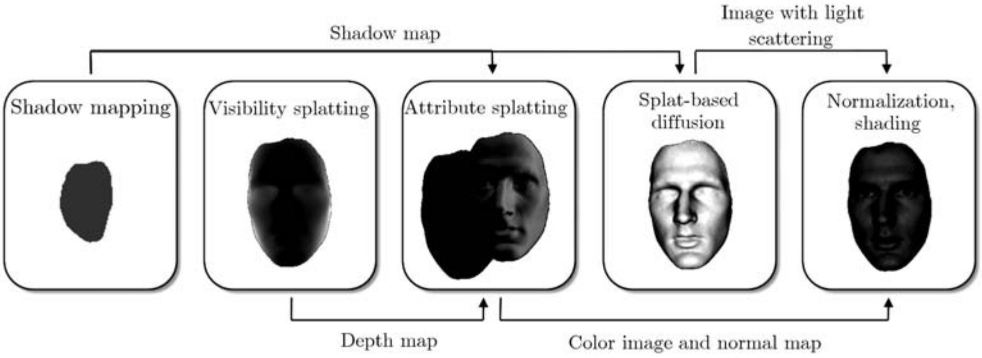

Figure 2 In order to simulate subsurface scattering, our rendering framework adds the two new passes of shadow mapping and splat-based diffusion to existing point-based rendering.

accumulates surface attributes, like color values and normal vectors. In the last pass, the image produced during the second pass is normalized and further per-pixel shading generates the final image.

We insert two new passes to the typical three-pass point-based rendering to make the appearance of translucent materials more realistic. These additional passes are shadow map generation and splat-based diffusion. Creating the shadow map precedes the three existing passes. The map that we construct contains the regions which are shadowed by the model's convex areas. It is generated by comparing distances from the light source to the surface of the model. Passes 2 and 3 in the new process are the first two passes of the original process, which determine depth information, color values, and interpolated normal vectors. In the fourth pass, splat-based diffusion is used to determine the effect of light diffusion. This will be explained in section 4.2. The final, fifth pass computes the actual color for each image pixel to produce the viewable image.

In order to render the reflective light from the skin surface, the specular reflectance is added to the calculated diffusion color within the presented rendering framework. In our study, we use the surface roughness and skin reflectance parameters of the specular BRDF model measured by Weyrich et al. [21]. However, the Kelemen Szirmay-Kalos model [24] is used instead of the Torrance-Sparrow model to speed up the calculation process.

4.2 Splat-based diffusion

Splat-based diffusion is an efficient way of approximating the light diffusion phenomenon inside a material in object space using splats. The assumption is that the diffusion of light is isotropic, and then its effect at a splat can be expressed as a Gaussian distribution applied to the radius of a splat. The overall diffusion effect across the surface is determined by combining the contribution of all the splats.

A diffusion color created by a single Gaussian function is usually inadequate to approximate a multi-layered diffusion profile for skin. We therefore use a sum-of-Gaussian technique developed by d'Eon and Luebke [4], in which six Gaussians of increasing radius as shown in Figure 3 (Top) are constructed on separate layers and subsequently combined by weighted addition in Figure 3 (Bottom). This is rendered in fourth pass of the process and the weighted splat-based diffusion technique resamples the diffuse color determined as the dot-product of the light direction and the surface normal. The resampled diffuse color is used for a splat color and the diffusion of light at the splat is approximated by surface splatting.

The computed diffuse color is represented as an image which is created by the linear combination of six images as shown in Figure 4. The first image is computed by the diffusion process of the normal map, which is the result of the previous pass. The other five images are iteratively generated using surface splatting with increasing radius of the splat. The light diffusion phenomenon is highly color dependent: red light scatters much farther than green and blue. When the sum of Gaussian weights is 1.0, the weights of blue and green are increased for the first few images made by using the small-radius splat. Conversely,

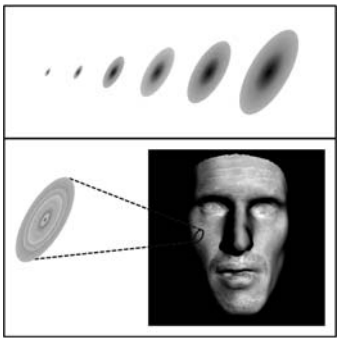

Figure 3 (Top) A Gaussian distribution applied to the radius of the splat. (Bottom) A diffusion profile is composed of six layers of increasing radius.

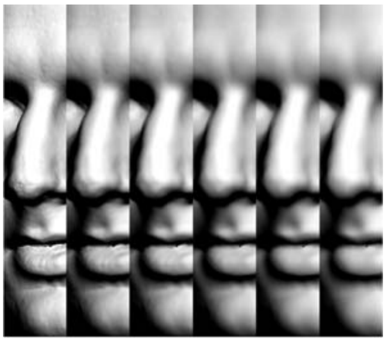

Figure 4 Six images computed with each of the six radii.

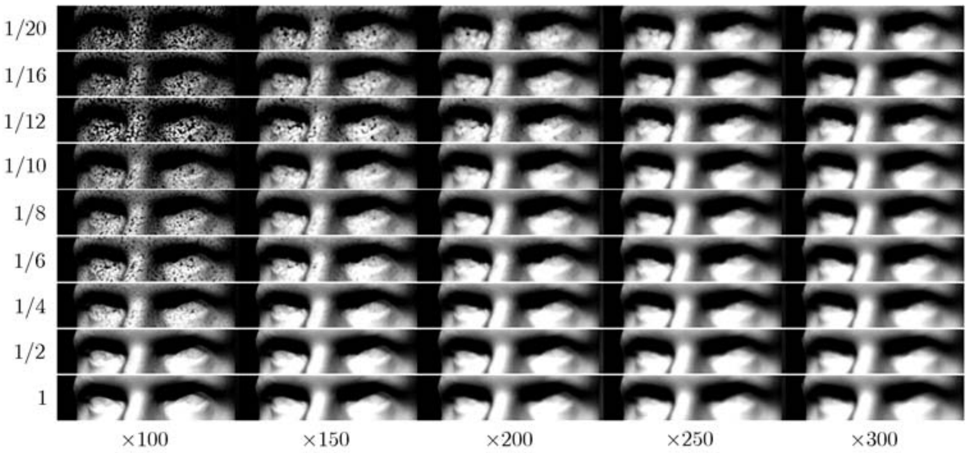

Figure 5 The horizontal axis represents the magnitude amplification ratio of the splat radius, whereas the vertical axis indicates the decreased ratio of the point number. Notice that the quality of the resulting image remains constant with only small number of points, as long as the radius of the splat is increased proportionally.

the weight of red is increased for the images generated by using the large-radius splat.

The process of the splat-based diffusion for making diffuse color images takes a large portion of the total processing time within the entire rendering framework. In the surface splatting process, as the radius of a splat increases, the process is slower because the number of the fragments projected on the screen space is increased. A notable fact is that even though the number of splats is decreased, the outcome does not change very much because the overlapping area between splats is larger. In other words, the detail characteristics of the model disappear because of many blurs. Figure 5 shows the results as radius of splats are varied. Such observation allows us to reduce the number of splats when the amplitude of the radius is large. Moveover, Figure 5 demonstrates how to manipulate the resolution to acquire a constant visual quality of the diffuse color images.

5 Results

We performed experiments on four high-resolution face models as shown in Figure 6. Our aim was to compare our technique with both existing point-based rendering methods and a mesh-based subsurface scattering technique. All the experiments were conducted on an Intel Core 2 Quad CPU Q6600 2.4 GHz PC with an nVidia GeForce 9800 GTX+ graphics processing unit.

Previous point-based rendering techniques do not support subsurface scattering, and as a result skin appears to be unrealistic, hard and dry. However, it is possible to add scattering of light and our approach allows more smooth skin appearance using the splat-based diffusion. In Figure 7, three different results from elliptical-shaped points rendering of the face model, high-quality surface splatting [18] and our rend-

Figure 6 Rendered results using our high-quality surface splatting with subsurface scattering.

Figure 7 (Left) Elliptical-shaped points rendering; (Middle) high-quality surface splatting; (Right) our results: high-quality surface splatting incorporating subsurface scattering effects.

Figure 8 We compare point-based and polygon-based rendering, with subsurface scattering. d'Eon and Luebke's approach allows realistic rendering of a face (Left). Our method (Right) creates much of the same look as the image achieved using their approach.

ering which incorporates subsurface scattering effects are compared. Note that the smooth light appearance is distinctive as we move to the right. The elliptical-shaped points rendering appears to be similar to flat shading since there is neither color nor normal interpolation between splats. Although the appearance of the two images on the right is relatively soft, the image from our approach appears to be more realistic than the rendered results without scattering effects. Given the fact that EWA splatting [6] is a software-based method, small holes are generated during the projective mapping process. On the other hand, although the Phong splatting shows better performance for low resolution cases, some aliasing often occurs since the technique does not use a screen space filter. The advantage of our approach is that it allows a more realistic rendering because the subsurface scattering effect is incorporated.

Comparison with polygon-based rendering methods. Figure 8 illustrates the different quality between two cases. The face image contains 683549 points and the surface scattering is applied to the identical face model. The left half of the face model adopts polygon-based rendering, whereas the right half does point-based rendering. The polygon-based rendering uses d'Eon and Luebke's method [4]. The conditions for two cases are identical except that the method of calculating the diffuse color is different. The splat-based diffusion technique provides almost identical visual quality to polygon-based rendering using the texture space diffusion technique.

As the proposed method linearly combines Gaussian in object space, the light diffusion is conducted without any distortion. Note that the splat-based diffusion case is identical to the case where the texture-space stretch correction is used to remove the distortion that occurred around the high curvature area on the facial surface.

6 Conclusions and future work

We have proposed a subsurface scattering method for point-based rendering that uses a sum-of-Gaussian. The surface splatting technique using splats was employed to combine the Gaussians in object space. We are able to render realistic light scattering within the skin surface by approximating a multilayer diffusion profile of skin. The quality of our point-based rendering is almost identical to that of the polygon-based rendering using the texture space diffusion. However, our method is currently not fully optimized in terms of speed. In the future, we plan to optimize the number of splats required to produce each diffuse color image, and to adjust the resolution using perception-based metrics. Furthermore, we plan to improve the performance by shortening the iteration of the splat-based diffusion during the generation of diffuse color images.

Although we apply the surface splatting with subsurface scattering to human facial skin in this paper, the same method can be used for various translucent objects. Since the diffusion profiles can be measured by analyzing scattering of laser or structured light patterns, any translucent object can be represented through the process of fitting a sum-of Gaussian to the diffusion profile. Thus, whenever any diffusion profile is available, the corresponding splat-based diffusion can be applied.

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