Development of a Patient-Specific BRDF-Based Human Lung Rendering for VATS Simulation

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Abstract. Video-assisted thoracoscopic surgery (VATS), referred to as the commonest minimum invasive excision for located T₁ or T₂ lung carcinomas, requires a steep learning curve for the novice residents to acquire highly deliberate skills to achieve surgical competence. Based on the bidirectional reflection distribution function (BRDF) physics-based rendering model, the aim of this study is to propose a virtual reality-based (VR) surgical educative simulator with realistic performance in visual rendering for human lung in VAST procedures. Patient-specific medical images and 360-degree dynamic surgical room environment are also being integrated in our training scenario. Finally, validation experiments are implemented on the virtual surgical simulator SimVATS framework, which demonstrated a high performance and distinguished immersion. This study may explore a new graphic rendering model for the VATS surgical education integrate with haptic and VR implementation.

Introduction

Benefit from the burgeoning improvement on computer graphics (CG) and virtual reality (VR) technologies, virtual surgery is considered as a method that can reduce the cost of surgical training for surgeons effectively. Yet, only few physics-based rendering are applciated in the medical field, especially the rendering of soft tissues in the human body. Furthermore, minimally invasive surgeries (MIS) usually accompany with a high risk due to the limitations in operating space, viewing angle, and lighting conditions. The visual properties of human soft tissues have a high dynamic range and there is individual pathological difference [1]. Therefore, virtual surgery requires higher requirements for the immersive reproduction and realistic visual effects as operation room (OR) scenes. Most current virtual surgical simulators focus on the interactions between trainees and virtual scenes and ignore realistic surgical environment and human tissue rendering. In consequence, trainees are constantly aware that they are in a fake virtual training environment, rather than the actual surgical process [2]. In this context, the physics-based rendering method is considered to be an effective way to provide more visual information. In addition, due to real training scenarios, virtual reality technology will also improve clinical effectiveness [3].

Related Works

In 1999, Marschner et al. proposed image-based BRDF [4], which is based on a specific location of the light source and the camera, using a photo and any geometric shape to sample the isotropic material. In 2004, Chung et al. introduced a method of retroreflective BRDF sampling in video bronchoscopy images [5], which allows the acquisition of BRDF, where light is always collinear with the camera,
and their goal is to render a view angle. In 2011, Cenydd et al. improved image-based BRDF to measure BRDF in the human brain [6]. Taking the space and time constraints into account of the surgery, they could only take five photos of the area of interest and the sampling was poor. In 2017, Qian et al. proposed a virtual reality framework for laparoscopic simulations [7], including the use of microfacet models for material rendering. VR applied in the medical field has dramatically boosted in the field of surgical planning, surgical navigation, and rehabilitation training [8]. Although VR has made great progress in the medical field, there have been major improvements in techniques and visual effects [9, 10]. However, these applications have neglected the effect of the operation room environment on the effects of surgical training.

**Methodology**

**Medical Image Acquisition and Geometric Reconstruction**

Medical image data is provided by the Thoracic Surgery Department, Yunnan First People's Hospital in China. CT images is form a 34 years old male in T2 stage of non-small cell lung cancer, with the high-resolution chest and abdomen scan (512×512×3172 and 0.51×0.51×0.50mm, by Siemens Corporate Research) images demonstrated the RUL tumor in Fig. 1 (a). Our 3D geometric reconstruction of the lung and chest models are based these medical data. We recorded a thoracoscopic video of the right upper lobe resection in OR for the image-based rendering and the synchronous panoramic video for the highly immersive OR environment reproduction (Fig. 2 (d)).

![Image](image1.png)

**Figure 1.** Patient-specific model processing for the visual rendering. (a) Original CT image import, (b) Marching cube-based 3D mesh reconstruction, (c) Simple texture rendering.

![Image](image2.png)

**Figure 2.** Steps of our method to build virtual surgery system. (a) Surgery video, (b) Geometry reconstruction, (c) Physical-based rendering, (d) 360° video, (e) Interactive test, (f) Highly immersed system.

The CT scan slices are the basis for a three-dimensional reconstruction of the lung and chest models. To reproduce the visual objects into the virtual environment, firstly, patients-specific CT images (DICOM) were imported to construct clinic simulation, segmentation functions like threshold
and region growing are employed here to the ROI extraction. After that, we invited 3 professional thoracic surgeons form the Yunnan First People’s Hospital to revise the auto-segmentation result with manual correction.

**Physics-Based Rendering**

The microfacet theory describes that on a microscopic scale, any surface can be described by many absolute smooth micromirrors, and the normal of each microfacet are different. The microfacet model can be decomposed into two parts: the diffuse reflection $f_d$ and the highlight reflection $f_s$.

$$f = k_d f_d + k_s f_s$$  \hspace{1cm} (1)

where $k_d$ and $k_s$ are the coefficients of $f_d$ and $f_s$.

The diffuse term $f_d$ uses the Disney model, following Fresnel's Law of Refraction, where the light experiences two refractions as it enters and exits the surface.

$$f_d = \frac{C}{\pi} \left(1 + \left(F_{g90} - 1\right) \left(1 - \left(n \cdot 1\right)^5\right) \left(1 + \left(F_{g90} - 1\right) \left(1 - \left(n \cdot 1\right)^5\right)\right)\right)$$  \hspace{1cm} (2)

$$F_{g90} = 0.5 + 2(v \cdot b)$$  \hspace{1cm} (3)

where $C$ is the color value, $n$ is the surface normal vector, $v$ is the vector pointing to the camera (observation point), and $l$ is the vector pointing to the light source.

For specular reflection $f_s$, its Cook-Torrance form can be described as:

$$f_s = D \frac{F_{DF} G_s}{4(n \cdot v)(n \cdot 1)}$$  \hspace{1cm} (4)

where $D$ is a normal distribution function that determines the appearance of the surface of the object, defines the highlight range, and the spot size. $F$ is the Fresnel item, generally using Schlick approximation. $G$ is a geometric attenuation term that describes the occlusion of the surface of the object.

In order to capture the real world better, we use the GGX distribution [11]:

$$B = \frac{a^2}{\pi(n \cdot h^2)(a^2 - 1) + 1^2}$$  \hspace{1cm} (5)

where $a = \text{roughness}^2$.

The Fresnel equation is complicated. In order to better deal with retroreflective, we make a Schlick approximation to the $F$ term:

$$F = F_0 + (1 - F_0)(1 - (n \cdot v))^5$$  \hspace{1cm} (6)

For the $G$ term, Heitz et al. [12] pointed out that using the Schlick model to approximate the Smith visibility function is not accurate enough. The highly correlated Smith function shows a better result. It can model the correlation between masking and shadows based on the height of the microfacet.

$$G = \frac{\chi^+(v \cdot h)\chi^+(1 \cdot h)}{\Lambda(v) + \Lambda(1)}$$  \hspace{1cm} (7)

$$\Lambda(x) = \frac{-1 + \sqrt{1 + \alpha^2 \tan^2(x)}}{2}$$  \hspace{1cm} (8)

where $\chi^+(a)$ is a step function When $a \geq 0$, $\chi^+(a) = 1$, when $a < 0$, $\chi^+(a) = 0$.

In thoracoscopic surgery, the endoscope is the only light source in the human body [13]. To reduce the impact of lighting calculations on system performance, we employed the image-based lighting
(IBL) algorithm. This method utilizes cubemaps instead of regular lighting in the environment. Therefore, we created a cubemap using a picture of the surrounding environment. Considering the complexity of the actual scene and thoracoscopy lighting, we have reduced the rendering based on deferred shading and the pipeline focuses on material rendering. Figure 3 shows an example renderer and overall structure rendering pipeline. First, we need the model of geometric reconstruction in Part 3.1, which was modified under the guidance of a surgical expert. Then we created textures such as diffuse maps, normal maps, etc. With Unity's ShaderLab, we have developed a lighting model and BRDF shader for virtual thoracic surgery. Finally, we conducted some optimizations and corrections.

**Creation of Virtual Reality Surroundings**

In the operation room of Yunnan First People's Hospital, we used a 360 degree camera to take a live video of the right upper lobe resection (Fig. 4) in place of the virtual reality operation room environment. The video is mapped to a sphere created on the game engine Unity. In addition, we use Unity Mesh to create a sphere based on the regular octahedron partition. Then, fix the SteamVR camera at the center of the sphere. We also created scenes in conventional thoracoscopic surgery such as the patient's body, and surgical instrument model in a virtual scene.

**Results**

We have established a highly immersed thoracoscopic virtual surgical training system based on the Unity platform, as shown in Figure 2. At the same time, we developed a BRDF shader suitable for thoracoscopic surgery. Our system run on a desktop with a Xeon E5 CPU and Quadro K5200 GPU. Under the supervision of surgical experts, we completed the test of the system. The results showed that the participants agreed that the system has a satisfied user experience. From Figure 5 (b) we can see the different shader rendering results in the same scene. On the left is the result of our
physical-based BRDF shader rendering developed for human organs and tissues, and on the right is the result of Unity's own standard shader rendering. According to the environment map and lighting model, we adjusted the relevant parameters. The rendering results after the correction are shown in Figure 5 (a).

![Figure 5](image)

Figure 5. Shading effects of different shaders in the same scene and rendering effect in system. (a) Corrected rendering, (b) On the left is a physical-based BRDF shader, and on the right is a standard shader built into Unity.

In addition, we tested our BRDF shader with a set of standard textures. As shown in Figure 6, Roughness and Specular do not show good performance. Compared to standard shaders, our BRDF shaders perform better in shadows and graphic occlusion.

![Figure 6](image)

Figure 6. Comparison of different shaders.

Table 1. Comparison of our custom BRDF shader and Unity standard shader in rendering costs.

<table>
<thead>
<tr>
<th>Item</th>
<th>Custom</th>
<th>Standard</th>
</tr>
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<tbody>
<tr>
<td>FPS</td>
<td>68.3</td>
<td>68.5</td>
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<tr>
<td>CPU</td>
<td>14.6ms</td>
<td>14.6ms</td>
</tr>
<tr>
<td>Batches</td>
<td>15</td>
<td>11</td>
</tr>
<tr>
<td>Shadow casters</td>
<td>6</td>
<td>2</td>
</tr>
</tbody>
</table>

We can compare the computational cost of our custom BRDF shader and Unity standard shader (Table 1). We can see that our custom BRDF shader and Unity standard shader basically have the same FPS and CPU response time during rendering. Although our custom BRDF shader has increased in Batches and Shadow casters, we have obtained high quality rendering result.
Future Works

In this paper, we have detailed a patient-specific BRDF-based human lung rendering for VATS simulation. This initial physic-based rendering method implementation and the integrated framework design provide an immersive platform for lung carcinomas surgical training and education. However, this our material rendering process consumes most of the computing resources, and the resolution of head-mounted virtual reality display devices is not high enough. In addition, biomechanical model of human soft tissue deformable simulation is also considered to be improve in our future research.

References


