Rendering of in-vivo Organs through Laparoscopy-based Sampling of BRDF

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Fig. 1. An image of a human liver captured during a laparoscopy as the input of our method (left). Approximation to organ geometry, the camera path and light position (middle). Global illumination rendering of a liver, based on the BRDF estimated by our method (right).

Abstract—While improved visual realism is known to enhance training effectiveness in virtual surgery simulators, the advances on realistic rendering for these simulators is slower than similar simulations for man made scenes. Among the various reasons for this, in vivo data is hard to gather and process. In this paper we propose the analysis of videolaparoscopy data to compute the BRDF of living organs and therefore provide plausible physics-based rendering of the biological tissue. Based on the interplay between light and organic matter recorded in video images, we propose the definition of a process capable of establishing the BRDF for inside-the-body organic surfaces. We present a case study around the liver with a full rendering pipeline, including global illumination simulations. Results show that despite the limited range of motion allowed within the body, the computed BRDF presents a high-coverage of the sampled regions.

Keywords—organic BRDF; high-coverage sampling; surgery simulation; patient specific; laparoscopic surgery;

I. INTRODUCTION

Computer Graphics (CG) has collected important results in the search for faithful virtual representation of scenes and behaviors in the environment as a whole. The increase of computational power seen in recent years has driven the implementation of visual appealing results in various fields of human activity. One of the most important beneficiaries of such results is Medicine. In particular, a vast field of study involves the development of techniques to make viable simulations of surgeries, focusing on anatomical fidelity of three-dimensional scenes, as well as the realism of the produced images. The graphical realism is essential for synthetic simulations in Minimally Invasive Surgeries (MIS), which are also well suited for virtual and augmented reality techniques since monitoring via camera is the primary tool for spatial orientation, while the doctor performs the surgery through small incisions in the patient. In Fig. 2 an example of the incision sites of a laparoscopy.

Fig. 2. Typical setup to the incision sites of a robotic-assisted laparoscopy to a cholecystectomy procedure.

Particularly for virtual simulators, there has been a lot of work focused on techniques to provide enhanced realism of the simulated scenarios, but with a strong focus on interaction, shape of organs, and physics-based dynamic behavior. Considering realistic rendering, however, it is clear to see that advances on rendering for these simulators is slower than

This work is related to a Master’s thesis presented in 2014/03.
similar simulations for man made scenes. There is therefore a huge gap of data and/or techniques which adequately deal with the natural world. Our solution proposes the rendering of living organs with a physically-based approach. Physically-based approaches use the concept of Global Illumination as expressed by Kajiya in his 1986 rendering equation and have also the potential of providing more visually faithful depictions of real scenes, since they are derived from first principles.

A key concept in global illumination is the Bidirectional Reflectance Distribution Function (BRDF). The BRDF for a given material expresses how a given incident light is reflected off the surface. For many objects, BRDFs can be measured with special equipments called Gonioreflectometers. For some natural objects, however, due to intrinsic reasons, it is not possible to measure the BRDF with a gonioreflectometer, and therefore alternative methods must be used.

Contributions: In this paper, we present a new technique to efficiently estimate BRDFs from in-vivo laparoscopic images, based on the work of Marschner. The idea is to derive the BRDF from a set of images (or video) taken from the material of interest. The results are limited, when compared with BRDFs measured with gonioreflectometers, but nevertheless useful. It is also a faster method, when compared with gonioreflectometers. Our work is aligned with recent efforts in the same area such as and , but with a major difference: we provide a high-coverage BRDF sampling protocol based on the laparoscopic images. We use the liver as a case study and present, for the first time, a full rendering pipeline providing global illumination rendering results for a living organ.

A. Related Work

Richard A. Robb’s research group has pioneered the idea of visualization of the interior of bodies with a collection of X rays for dogs, and his work is the basis for current Computed Tomography systems. Sunguroff and Greenberg presented the first computer graphics simulation of a human brain for brain tumor surgery planning. They used Gouraud shading and Blinn’s illumination model for rendering. Both Gouraud’s and Blinn’s models have well known limitations when dealing with organic materials. Barillot et al. used specialized medical equipment to represent thin structures, such as blood vessels, to increase the quality of images for medical applications.

Neyret and Cani created procedural textures based in Worley’s processes and Perlin’s noise in order to simulate the visual appearance of hepatic tissue. They particularly addressed distortions caused by texture mapping and also seamless merging of triangular textures with a Voronoi type construction. Neyret and colleagues improved on previous work by enhancing the specular effect with a simplification of Environment Mapping by drawing a ring with size and thickness parameterized by variables such as the distance from the 3D model to the light source and the surface’s orientation. In this way they were able to achieve a wet look for the virtual liver using Phong’s illumination model. In 2003 Stoyanov and colleagues surveyed the application of computer graphics techniques in MIS, emphasizing the great opportunity for improvements in the field. Elhelw et al. argued that local illumination models such as Phong’s do not correctly account for light reflecting off organic materials, and introduced an optimization of Bump Mapping to represent roughness levels for organic tissue based on pictures of real tissue. Besides, they have used a refraction map to improve transparency effects.

Chung and colleagues used image-based BRDF acquisition techniques from video bronchoscope images. Their goal is to render views for a specific patient. The derived BRDF data was used to synthesize texture maps free of illumination artifacts, and also to render novel views not originally captured in the bronchoscopy video. With a similar approach, Cenydd et al. proposed a method for BRDF acquisition for the brain to be used in simulators of neurological surgeries. They were able to customize visual aspects of the rendering while still not using a global illumination approach. With a different goal of improved 3D reconstruction of human organs, Malti and Bartoli introduced a simplification for BRDF acquisition through which they estimate parameters for analytical illumination models.

From the above review, we notice that only recently solutions addressing the need for BRDF data appeared. However, these results did not fully recovered a BRDF since their methods of sampling considered only the portion where the light is collinear to the camera. Besides, they did not provide results based on global illumination algorithms. We propose a full solution which first computes BRDFs from videos and later renders the organ with a global illumination approach.

II. Method Overview

The challenging environment of a laparoscopy requires special care with the surgery protocol in order to measure a BRDF of a living organ which we divided into two parts. The sampling step comprises gentle-adaptations in the conventional laparoscopy in order to preserve organ geometry and to obtain the best possible coverage to the BRDF. In a second step, we treat the representation and rendering, defining the BRDF data according to systems for rendering, mainly those which implement global illumination algorithms.

Below we present our solution for measuring BRDFs and rendering in-vivo organs.

A. Sampling

In this stage, images are acquired during a laparoscopy procedure and then sampled to build a BRDF. The basic idea was defined by Marschner. Our contribution was to adapt the procedure to a very restricted environment with limitations in time and space. We defined a protocol for measuring the BRDF for the liver during a Cholecystectomy. This protocol maximizes the coverage of the images in order to enable high coverage of the reflection hemispheres as possible.

We adopted two complementary configurations in our method, illustrated in the Fig. In the first, the camera
and light move together, sampling the BRDF portion that is reflected in the light direction. In the second, we use two telescopes so that the light is inserted by a different portal and the camera moves freely. In this case, the light source must be placed at a wide angle as possible with the camera, but less than 90 degrees and not occluded. In both configurations, we used a 30° telescope and performed a synchronous revolution movement of the camera lens by the combination of axial translation and two rotations. With this movement, the lens orbit around the organ that stands still, performing a semi-revolution (a 180° arc on a section plane of the organ) combined with a local rotation to orient the lens towards the organ, as depicted in Fig. 4.

![Fig. 3. Sampling setup to get BRDF behavior where the incident light is collinear to outgoing direction (a). Complementary configurations to sampling additional reflection angles (b).](image)

In order to compute the BRDF from images, we need to track the camera and light positions for all video frames obtained from laparoscopy. We also need a geometric model of the organ. The goal of this procedure is to get a set of animations correspondent to the surgery videos, then associate color information to geometric data for each pixel of our sampling set.

For camera tracking our approach is based on the work of Palma et al. [16]. We use the method KLT (Kanade-Lucas-Tomasi) [17] to calibrate between camera and geometry using the video itself. KLT analyses the brightness variation in a characteristic point available in two sequential image frames to estimate affine transformations that define the camera motion. To approximate the organ geometry, we used a canonical geometry reconstructed from the segmented photographs of the Visible Human male dataset [18]. We edited the geometry manually so that it conforms with a set of frames selected from the video, as illustrated in Fig. 1. Similar geometry reconstructions could also use actual patient data to increase accuracy.

Finally, we need light source estimations. When light and camera move together, the solution is trivial as the camera tracking proposed above can also be used for the light. When two telescopes are used, and given the space constraints within the body, we assume that the light distance to the organ is similar to that of the camera. We then interactively adjust the light position in a virtual model of the surgery until the specular reflection coincides with that from the video for the set of frames. Remember that light is fixed in this setup.

Once the geometry, camera and light information are available, we can extract for every pixel the radiance information $L_e$ reflected by the organ surface to that pixel. Together with this value we also have the four angles which define the incoming $(\theta_i, \phi_i)$ and outgoing $(\theta_e, \phi_e)$ directions. In the animations, the incoming and outgoing angles are mapped as pixel colors, representing the scene geometric data to the same surgery video. For an incoming light map, the R and G canals of the image are the $(\theta_i, \phi_i)$ tuple. In an outgoing light map, the R and G canals of the image are de $(\theta_e, \phi_e)$ tuple, as depicted in Fig. 5.

![Fig. 5. A frame of the surgery video (a). Correspondent outgoing light map (b) and incoming light map (c).](image)

### B. Representation and Rendering

Once the BRDF is computed from the previous step, we need to be able to efficiently work with the data. There are basically three possibilities for BRDF representation: (i) as a table. Most commonly used, but not very effective since it requires a lot of space to store and longer times to process; (ii) as a kd-tree. Used in some rendering plataforms to speed the access to the data; (iii) the BRDF is fit to an analytical model. According to Ngan [19], a good choice for a BRDF analytical model is the isotropic version of Ashikhmin model [20]. This is the model we used in our experiments. The model is a sum of a diffuse part and a specular part. The diffuse part follows Lambert’s law. The specular is modeled analytically with main parameters $n$ and $F_0$. $n$ controls the shape and intensity of the specular lobe whereas $F_0$ controls the Fresnel effect. We use Levenberg-Marquardt method to numerically approximate the Ashikhmin model parameters.

Global illumination renderers are still expensive for real-time simulations. Therefore there are hybrid approaches which improve on local illumination models with the BRDF data [6] [16]. We, however, are interested on global illumination approaches. Our results indicate that the current state of the art in both software and hardware will make possible to
run in realtime first order approximations of the light-matter interaction soon.

There are many implementations of global illumination algorithms according to the general principles introduced in Kajiya's rendering equation. They differ on the assumptions and phenomena they are able to model. In our work we have used three possibilities: PBRT [21] and Mitsuba [22] and Disney BRDF Explorer [23].

III. EXPERIMENTS

To get laparoscopic videos according to our sampling requirements, we rely to the medical partnership of the Clinical Hospital of Porto Alegre, under supervision of the doctor Leandro Totti Cavazzola [24]. Along the development of this work, we participated of three surgeries and we performed the BRDF sampling according to our method. In this paper, we describe the results related to the second surgery, providing images generated through global illumination algorithms and quantitative analyses of the sampling coverage.

A. Image Resolution Optimization

The standard resolution of the laparoscopic camera used in our experiments is 1920x1080. However, we generate a total of 300 frames from the video surgery divided into two sets (one for each configuration of BRDF sampling). Thus, the table generated based on such data can easily produce files around 25 GB. To avoid this we performed an experiment in order to identify the best resolution for the set of images. Our approach is based on the systematic fitting of the isotropic version of the Ashikhmin model through reductions in the resolution of a particular image (for complete description of the Ashikhmin model, please refer to [25]). Fig. 6 shows little variation between the values of the n parameter when using the original resolution and a resolution of 240x135. For the parameter $F_0$, we can see the same behavior illustrated in Fig. 7. Thus, in our experiments, we adopted the 240x135 resolution and reduce such images of the original video by the Lanczos re-sampling method.

B. In-vivo Liver based Experiment

We applied our procedure to produce the rendering results depicted in Fig. 8. The liver was rendered with PBRT, first with the BRDF as a table (a), and then with the BRDF represented analytically with the Ashikhmin model using the approximated parameters values presented in Table I.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value in (R,G,B)</th>
<th>Parameter</th>
<th>Value in (R,G,B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>d (diffuse)</td>
<td>(1.0, 0.55, 0.51)</td>
<td>n</td>
<td>(10.27, 39.75, 42.8)</td>
</tr>
<tr>
<td>s (specular)</td>
<td>(1.0, 0.13, 0.11)</td>
<td>$F_0$</td>
<td>(1.0, 1.0, 1.0)</td>
</tr>
</tbody>
</table>

Fig. 8. a - Rendering with PBRT. BRDF expressed as a table. Rendering time 432 secs. b - Rendering with PBRT. BRDF expressed analytically. Rendering time 1 sec.

Considering global illumination interactions, our method provide the rendering of images as in Fig. 9 where different environment maps change the final aspect of the liver model through the interaction between BRDF and the light conditions.

In this experiment, the BRDF measured through our method present low specularity, probability due to the subsampling which still occurs in a laparoscopic context. In Fig. 10 the specular lobe of an in-vivo liver BRDF is presented.
IV. RESULTS

To better assess the plausibility of these results, we have compared our synthetic images with real images from the same camera and lighting configuration. In Fig. 11 the real liver and a synthetic image are shown side by side. Although the high frequency information is lost, as with any BRDF, the intensity of the reflected light is very similar. We then used the correlation metric to compare the histograms for the two images. Similarity is higher than 99%. In a predictive approach, we perform the same analysis using a video frame which was not used as a BRDF sample. Nevertheless, the result in Fig. 12 is still quite similar.

Moreover, we have measured how well our sampling method acquired the BRDF data. Fig. 13 shows the hemisphere around a point with the coverage obtained experimentally. Despite the heavy motion constraints imposed by the laparoscopy setup, results show that our method covered 21.28% of the total area for the incoming light directions and 22.36% for the outgoing directions. Considering all limitations, this is a high coverage.

V. DISCUSSION AND CONCLUSION

While the BRDF of man made objects has been captured for decades, there is a huge gap of data and/or techniques that adequately deal with the natural world.

In this dissertation we have presented for the first time a full pipeline for acquiring BRDFs from laparoscopic videos of a living organ. We then used the captured data to render a synthetic organ in a global illumination framework, demonstrating the feasibility of the approach. Our main contribution is thus
a sampling protocol for living tissue BRDF that provides high coverage for the sampled organ curvature. The method preserves conventional laparoscopy equipment and preparation, adding only 5 minutes in the beginning of the standard surgical procedure. Camera tracking based on KLT provides freedom for the surgeon to perform revolution movements without the need for additional equipment.

One limitation is that our method produces sample concentration due to the restricted camera and light range of motion. This behavior may cause sub-sampling of the specular lobe. Concentration also causes superposition, with many different values being sampled for the same parameters due to the heterogeneity of the biological tissues. Another limitation is that BRDFs are ideally sampled in dark controlled environments without reflections. This is impracticable in the confined environment of the laparoscopy. So the method described here does not deal with the interferences on the values of the sampled BRDF caused by ambient lighting propagated inside the body by interreflexions. Finally, another limitation regards the camera distance to the organ surface. When it is too close it is not able to frame high frequency parts of the scene, which penalizes the KLT tracking.

There are many avenues left for future work. The use of additional portals for sampling, generating a higher number of camera-light positions combinations, can provide higher coverage of the reflection hemisphere being an element to compose a future experiment. Besides, as this dissertation focused on physics based rendering for surgery simulators, a better approximation for the geometry of the sampled organs can be made based on anatomical reconstruction of tomographical patient data. This can improve sampling accuracy and enhance the coverage analysis. Finally, the use of KLT to track the light source as well, configuring a scene registered by two cameras at the same time, is a viable alternative to replace the manual adjustment used in this work, improving the data consistency.

While sampling BRDFs from living organs is an important step, BRDFs are first order approximations to the full light-matter interaction. Better approximations of the light-matter interaction are possible with Spatially Variant BRDFs (SVBRDF) and we plan to address this soon. Also, abdominal laparoscopy techniques provide easy access to many organs. Design decisions made about this class of MIS can be adapted to minimally invasive techniques related to other areas of the anatomy. Also, organ BRDFs can be customized according to specific patient’s conditions (age, sex, weight, disease, . . .) to provide a variety of simulated conditions. This is an exciting possibility in the important area of Patient-Specific Virtual Reality.

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