Simultaneous Visualization of Preoperative Planning Models and Intraoperative 2D Ultrasound for Liver Surgery

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Abstract

This paper introduces new techniques for simultaneous visualization of preoperative planning models and intraoperative 2D ultrasound for open liver surgery. The driving motivation for our work is to improve the visual presentation of a moving ultrasound plane within a complex, interweaving three-dimensional model of hepatic vascular structures. Major drawbacks of existing systems are occlusions of the ultrasound plane by the planning model and fade-out of crucial context information. Our system allows the surgeon to focus on the ultrasound image while perceiving context-relevant planning information without discarding important morphological information and depth cues. The contribution of this paper is a GPU-accelerated rendering pipeline including new illustrative visualization algorithms for focus & context rendering, distance and intersection accentuation, as well as a hybrid technique for high quality silhouette and hatching stroke generation.

Categories and Subject Descriptors (according to ACM CCS): J.3 [Life and Medical Sciences]: Health I.3.3 [Picture/Image Generation]: Bitmap and framebuffer operations

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1. Introduction

Living donor liver transplantations and tumor resections from the liver are risky and demanding surgical interventions. Understanding the morphology and branching pattern, as well as the spatial relations between hepatic vessels, is crucial in order to prevent healthy organ regions from being cut off from blood supply and drainage. Currently, therapy planning software provides preoperative 3D planning models of vascular structures with additional planning information, like a color encoded risk analysis.

Intraoperative ultrasound is commonly used to support navigation of surgical instruments, as well as verification and adaption of planning strategies. One evident step to improve liver surgery is to visualize the planning results together with images delivered by a ultrasound-based navigation system. This support provides valuable information, such as the relative position of surgical instruments to important liver vessels or boundaries of vascular territories [LEH*04]. An adequate visualization of the ultrasound plane relative to the preoperative model facilitates the navigation for the surgeon and is beneficial for precise liver surgery.

The main contribution of this paper is a concept for simultaneous visualization of preoperative planning results and navigated 2D ultrasound. We introduce a new visualization approach - specified in a GPU-based rendering pipeline - which allows a focusing view on the ultrasound image while perceiving context-relevant planning information and depth cues. The paper is organized as follows: First, we review related work in the field of vascular surface reconstruction, illustrative rendering and focus & context visualization. Subsequently, we introduce the above mentioned pipeline, including new algorithms for high quality silhouette and hatching stroke generation, distance and intersection enhancement, as well as new approaches for focus & context rendering. Finally, we present results and discuss future work.

2. Related Work

A variety of surface reconstruction methods for vascular structures that take central axis and radius information as input have been developed. *Explicit modeling* methods apply concatenated graphic primitives such as truncated cones [HPSP01] or are based on subdivision surfaces [FWB04]. General problems of these methods are discontinuities and overlapping surfaces, which primarily appear at branchings. To overcome these problems we use a *implicit modeling* technique based on convolution surfaces, which represent the radii of vascular structures through careful selection of convolution filters [OP05].

Since we draw on work in the field of nonphotorealistic and illustrative rendering, we review related methods in these areas. Based on traditional illustration techniques, a variety of nonphotorealistic methods have been proposed to apply silhouettes and hatching strokes in order to increase expressiveness of illustrations [SS02]. While the field of nonphotorealistic rendering is more concerned with imitating artistic styles in an automated way, illustrative rendering goes one step further and applies these techniques to enhance visual comprehension [BGKG06]. There exist advanced illustrative rendering techniques for hatching stroke generation on botanical trees [DS00] as well on vascular structures [RHD*06]. We got inspired by a sequence of user studies accomplish by Interrante et. al [IFP97]. They researched the effect of displaying surface texture in combination with multiple overlapping transparent surfaces and showed that nonphotorealistic techniques are an adequate solution to support evident recognition of layered surfaces.

Focus & context techniques have often been used to automatically enhance important information in an image. Bruckner et al. [BGKG06] developed a context-preserving volume rendering model using a function of shading intensity, gradient magnitude, distance to the eye point, and previously accumulated opacity to selectively reduce the opacity in less important data regions. Extending methods automatically determine the most expressive view controlled by changes in the importance distribution among features in a volume data set [VFSG06]. While previous focus & context techniques have mainly been developed to accentuate parts of a volume data set, our method is based on a surface presentation of interweaving planning models, while setting the focus of attenuation on a moving ultrasound plane within these models. Further, we aim at improving spatial perception by extending current illustrative rendering techniques.

3. Methods

In this section, we discuss requirements for a simultaneous visualization of preoperative planning models and intraoperative 2D ultrasound for clinical purposes and present a GPU-based rendering pipeline that addresses these problems.

3.1. Requirements

In case the ultrasound plane is located inside the liver, occlusion of the ultrasound plane by the planning model (vascular systems, tumors, organ surfaces) is an inevitable problem for the applied visualization technique (Fig. 1). Presenting the ultrasound image without planning data in a second window results in time-consuming comparisons for the observer because necessary information is not presented in one single image. Applying transparency or clipping operations on occluding objects removes important context information and results in a loss of spatial information and clearness. To address these problems, we define three guiding requirements to ensure clinical applicability of our methods:

- **Orientation Aid**: Spatial relations between ultrasound plane and planning data should be clearly perceivable without rotating or translating the camera.
- **Diagnostic Usability:** While the whole visualization is presented in one single view, ultrasound information should always be visible, even if it is potentially occluded by planning data or parts thereof.
- **Error Identification**: Since current intraoperative registration methods make a compromise between real-time and error-prone computation, registration errors should be visualized precisely.

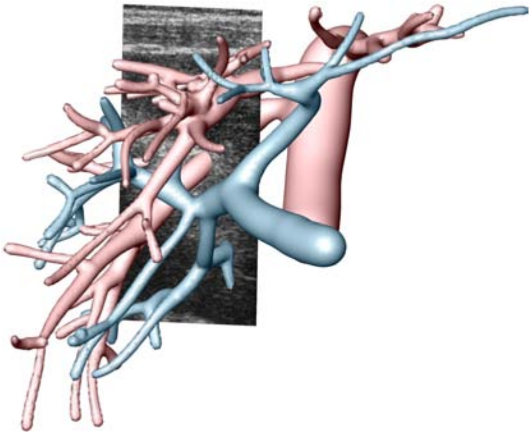

Figure 1: *Opaque visualization of a vascular system from the liver and a 2D ultrasound image. In this representation it is impossible for the surgeon to detect structures on the ultrasound plane because it is occluded by vessels.*

3.2. Rendering Pipeline

The fundamental idea of introducing a new pipeline is to provide a visualization in one single view by combining three extended rendering techniques. Therefore, we embedded the methods described in this paper in a GPU-accelerated rendering pipeline. This pipeline consists of the following four steps in which the first three steps directly address the prementioned requirements:

1. Silhouette & hatch stroke generation
2. Focus, context and mask image generation
3. Intersection contour generation
4. Compositing in screen space

Figure 2 illustrates these main steps concerning our requirements. In the following four sections, we describe the methods within these steps in detail.

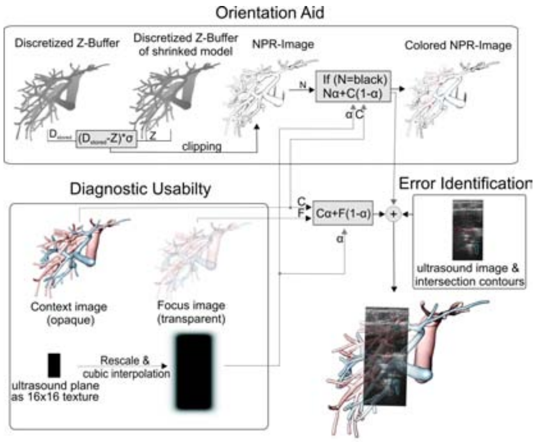

Figure 2: *Pipeline overview showing intermediate rendering results together with the associated requirements.*

3.2.1. Silhouette & hatch stroke generation

While silhouettes indicate the orientation of a surface perpendicular to the line of sight, hatching strokes can be used to emphasize slight changes in surface orientation (light interaction) or characteristic features such as curvature or discontinuities. We found that transparent layered surfaces in combination with shape-accentuating strokes are an adequate representation for objects that occlude the ultrasound plane. This gives a context-preserving view of the ultrasound image. Furthermore, we suggest varying the line width of silhouettes depending on the distance to the ultrasound plane to support depth perception.

In a first step, we render the depth values D_{stored} of the vessels into an off-screen texture. While D is the relative distance between the current vertex and the ultrasound plane, and R describes the diameter of the bounding sphere, we use a vertex shader to translate all vertices of the model by the factor $\frac{D}{R}$ in opposite direction to their normal vector. This causes a shrinking of the model depending on the distance to the ultrasound plane. The corresponding fragment shader computes the difference of the current depth value Z and D_{stored} which delivers a *distance encoding silhouette* in image space precision, i.e., the thickness decreases with increasing distance to the ultrasound plane.

We extend the method by applying hatching strokes within the same rendering step. Specifically, we apply a discretization function to both z-buffer images to generate two stair functions. Since the stairs of both images overlap due to the distance-depending translation of $\frac{D}{R}$, we receive high quality hatching strokes. This technique has already been described in [RHD*06]. Since differences are very small, we multiply the values by a scale factor σ to map them onto the range 0 to 255. In addition, aliasing effects in the image are reduced by applying anti-aliasing to areas of the image representing silhouette and hatching strokes. Furthermore, we set another depth cue by clipping all strokes located on the side of the ultrasound plane that is opposed to the camera.

3.2.2. Focus, context and mask image generation

For the generation of the focus and context images we render the colored and lit planning models onto two off-screen textures F and C. For F, opacity is decreased via Depth-Peeling to assure correct order independent transparency rendering [Eve01]. Then, these two images are blended using an 8-bit mask image.

Since the focus lies on the ultrasound image plane, we create the mask by first rendering this plane with disabled texturing onto an off-screen texture. Using this mask to combine F and C would lead to an abrupt change in different rendering styles at the border of the ultrasound plane. This causes a wrong spatial interpretation due to receiving the impression that the ultrasound plane occludes the vessels. We found that a gradual transition between focus and context images avoids this misinterpretation. To achieve this, we first render the ultrasound plane onto a low resolution buffer. When sampling from this texture, we use fast bi-cubic interpolation as described in [SH05] to obtain a smooth gradient. Thus, we avoid several blurring passes which are required when a higher resolution is utilized. The jaggies due to the low resolution do not impact visual quality.

3.2.3. Intersection Contour Generation

The generation of intersection contours is the only step which is computed by the CPU. This is done by first cutting an image representing of the ultrasound plane out of a three-dimensional binary vessel-mask (multiplanar reformation). Then, the well-known marching squares algorithm is used to find all iso-contours on that image. Contours are then rendered as a line-strip together with the focus image.

3.2.4. Compositing in Screen Space

By now we have generated the following off-screen textures:

1. NPR image N (silhouette and hatching strokes)
2. Focus image F
3. Context image C
4. Mask image M

The fragment program starts by computing the output color col_{Model} using a convex combination of the current F and C samples. The value sampled from the mask image M is used as the weight α. Recall that we use bi-cubic interpolation when sampling from M to achieve a smooth transition between F and C. Next the program computes the contribution from N to the current fragment color. If the sample of N is black the program outputs col_N instead of col_{Model}. col_N is determined by blending black with the color of C using α. Thus the silhouette and hatching strokes in the focus view are colored and illuminated depending on the light settings used to render C.

4. Results and Discussion

In this contribution we present interactive methods for simultaneous visualization of preoperative planning models and navigated 2D ultrasound. The work is guided by requirements that ensure the clinical applicability. Our GPU-accelerated visualization pipeline allows the surgeon to have a focus-view on a moving ultrasound plane within a complex, interweaving three-dimensional model of hepatic vascular structures (see Fig. 3). To improve orientation ability and distance perception, we included additional depth cues through new illustrative visualization algorithms.

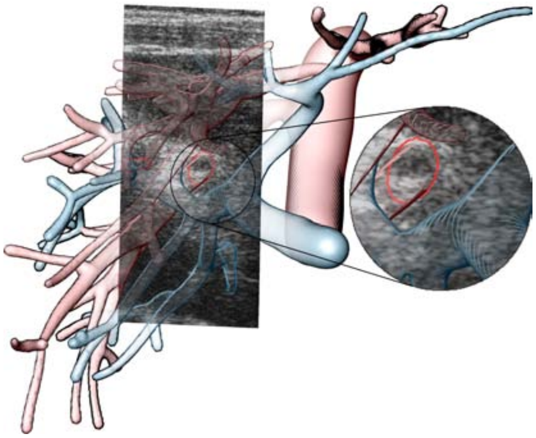

Figure 3: *Intraoperative focus & context visualization of preoperative planning data and intraoperative 2D ultrasound generated with illustration techniques described in this paper. The close-up view on the right hand side shows highlighted intersection areas and depth-accentuating hatching strokes. While silhouettes encode the distance to the ultrasound plane, a gradual transition from opaque to transparent rendering (around the focused ultrasound plane) avoids misinterpretation of spatial relations.*

With a prototype implementation of our pipeline on the developer platform MeVisLab we achieve interactive framerates (16fps on a GeForce 7900 GT) with a 2 Ghz CPU using a model with 203k vertices, four depth-peel passes and one anti-antialiasing pass. We expect real-time framerates after optimizing the code. Since our system uses a manual rigid registration approach, which showed no adequate accuracy for clinical use, we will extend our system by an intensity-based elastic registration. Furthermore, we expect additional input from a quantitative user study that is currently carried out in cooperation with clinical partners.

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