

Advanced Visualization Techniques for Laparoscopic Liver Surgery

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Abstract

In order to make it easier for the surgeons to locate tumors during a laparoscopic liver surgery, and to form a mental image of the remaining structures, the 3D models of the liver's inner structures are extracted from a pre-operative CT scan and are overlaid onto the live video stream obtained during surgery. In that way the surgeons can virtually look into the liver and locate the tumors (focus objects) and also have a basic understanding of their spatial relation with other critical structures. Within this paper, we present techniques for enhancing the spatial comprehension of the focus objects in relation to their surrounding areas, while they are overlaid onto the live endoscope video stream. To obtain an occlusion-free view while not destroying the context, we place a cone on the position of each focus object facing the camera. The cone creates an intersection surface (cut volume) that cuts the structures, visualizing the depth of the cut and the spatial relation between the focus object and the intersected structures. Furthermore, we combine this technique with several rendering approaches, which have proven to be useful for enhancing depth perception in other scenarios.

1. Introduction

During the past years gradually more surgeries are performed using laparoscopic techniques. During the surgery an endoscope camera transmits high quality video streams to high resolution monitors in the operating room allowing the surgeons to perform the same tasks as in open surgery. However, the endoscope video stream only provides visualization of the surface of the organ without giving information for the critical inner structures. Computer Assisted Surgery (CAS) is the concept of performing laparoscopic surgeries using computer technology. In CAS the first step is to create a 3D model that reproduces in great accuracy the geometry of the patient's organ. This can be done through a number of medical imaging technologies, with Computed Tomography (CT) being the most widely used due to its high accuracy. The 3D models reconstructed from CT are then uploaded into the computer system and rendered on screen.

In CAS surgeons also have the ability to use a navigation system that can register the used surgery instruments in relation to the 3D models in real time. By overlaying the 3D models on the live endoscope image, surgeons have the ability to reference the position of the surgical tools in relation to the 3D models and simultaneously with the patient's organ.

However, the representation of the 3D models have to provide a clear view of the critical areas (tumors and cysts), as well as correct depth perception and spatial information between structures. Within this paper we focus on enhancing the visualization of an augmented reality navigation system providing a more focused view of the areas where tumors are placed and better depth and spatial relation between them and their surrounding structures.

2. Related Work

Overlaying the anatomical structures on to the live endoscope image is not sufficient to ensure a good visual result. In computer graphics and especially in medical visualization one of the most important parts is to let the user perceive the spatial relationship between the objects in a 2D display. There are different techniques that allow users to estimate distances such as shading, contours, shadows, aerial perspective, texture gradients etc.. The depth perception is enhanced using halos that highlight the edges of certain structures [BG07] while depth perception is also influenced by different lighting parameters [TI09]. Lighting and shading are important as far as the visual feedback for space and depth perception and the impact of different luminance

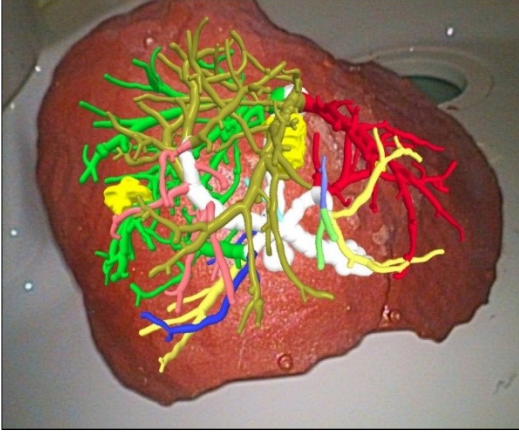


Figure 1: Illustration of the non-enhanced overlay of the 3D models on to the live endoscope image.

patterns are studied. Wagner compared different depth cues and their impact on depth perception [WFG92]. Different techniques that do not depend on transparency which can lead to errors and provide visibility of the focus structures have been developed and are referred to as smart visibility [VG05]. Smart visibility techniques rely on selectively removing structures or cutting into them. These techniques manage to preserve a high quality visual result despite the spatial deformations. Krüger et al. implemented a smart visibility technique by applying ghosting that fades out all the structures that lay in front of the tumors, called Clear View [KSW06]. The visibility to specific structures can be also assured by cutting into a 3D model, a technique that provides also depth perception by visualizing the depth of the cut. Such techniques are referred to as volume cutting. Diepstraten et al. present various approaches to generate cut-aways to allow a clear view into a solid object [DWE03]. Two different techniques are presented called cutout and breakaway. The former will remove a big part of the exterior of a geometry to reveal hidden geometries, while the latter will create a cutout in the shape of the hidden object. Rautek et al. used the tumor's silhouette to create the cut's shape providing information for the tumor's shape and the structures that lay in it but not reliable information for the depth of the cut [RBG08]. Using the Maximum Importance Projection the structures are cut by cones to visualize the depth of the cut and also the spatial and depth relation between the structures that lay inside the cones [VKG04].

3. Visualization Enhancements

To improve the non-enhanced overlay of the 3D models on to the live endoscope video stream (see Figure 1), the following visualization techniques were applied with the goal to enhance the depth perception as well as the spatial comprehension of the focus areas.

3.1. Blending and Environmental Depth Cues

In the overlay shown in Figure 1, the 3D models are perceived as the top layer and the endoscope image the bottom layer. It is clearly visible that 3D models seem to float over the liver's surface. In order to give the feeling that the 3D models lay underneath the liver's surface a blending mode has to be applied for both layers. After testing different modes, the screen blend mode managed to produce a result that suits the current case. With screen blend mode the colors of both layers are inverted, then multiplied and then inverted again according to the following equation:

$$f(a,b) = 1 - (1 - a) * (1 - b) \quad (1)$$

where a and b are the two layers. This blend mode does not distort the colors of the two layers, kept the main color gamut of the scene and also produces a brighter but not too bright image in contrast to the other tested blend modes.

Another downside of the current situation is, that the intensity of the colors of the 3D models as seen in the overlay is the same no matter if they are closer or further from the camera. In computer graphics in order to enhance the depth perception of a scene, techniques that simulate the environmental depth cue (atmospheric/aerial perspective) are often used [War12]. That refers to the decrease in contrast of distant objects in the environment. In order to simulate the environmental depth in the laparoscopic scenario, the inverted depth values of the 3D models are added to Equation 1:

$$f(a,b) = 1 - (1 - a) * (1 - b * b_inverted_depth) \quad (2)$$

3.2. Edge Detection

Due to the applied blending, the inner structures lie now below the liver's surface. Unfortunately, thus also the spatial relation of the 3D structures has become harder to detect due to the blending. By applying an edge detection algorithm and drawing the contours of the structures, the spatial relation can be enhanced. The edge detection is applied before the blending on the rendered 3D models. As the scene is not that complex most of the edge detection algorithms will produce quite a good result [JS09]. A basic average intensity difference edge detection algorithm is applied in a fragment shader. The algorithm traverses all fragments and averages the adjacent intensity values, creating a mask with the averaged RGB colors of all the neighboring pixels. Then, the intensity differences between the neighboring pixels are averaged:

$$I_x = \frac{|I_1 - I_7| + |I_0 - I_8| + |I_3 - I_5| + |I_6 - I_2|}{4} \quad (3)$$

Finally, applying a user defined threshold to the current

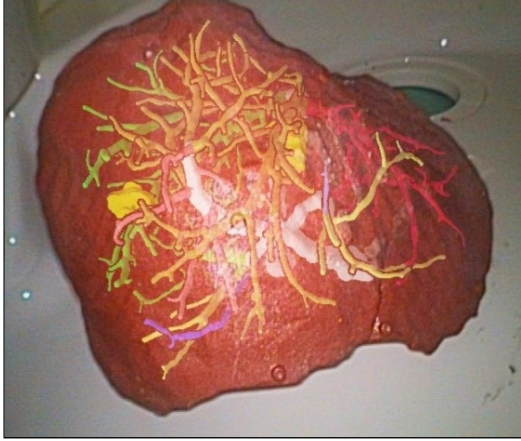


Figure 2: Adjusted screen blend mode using the edge detected models and simulating the environmental depth cue using the depth inverted depth values.

pixel's final intensity value will determine whether or not that pixel is an edge. The edge detected models are then added in Equation 2:

$$f(a,b) = 1 - (1 - a) * (1 - b_{edge_det} * b_{inv_depth}) \quad (4)$$

The result after applying the described blend mode together with the edge detection can be seen in Figure 2.

3.3. Focus+Context Visualization

During a laparoscopic surgery the surgeons have to focus on the areas where the tumors are located. The location of the tumors, from now on referred to as focus objects, and the proximity to critical surrounding areas such as main blood vessels is extremely important to the surgeons for treatment decisions. The liver contains a very complicated network of vessels that most of the times occlude the focus objects. In order to enhance the depth and spatial perception of the focus objects with their surrounding structures, a cut volume can be created using a cone placed on the positions of each focus object. When a cone is intersected in different spots, the depth comparison between the intersected points is easier due to its angular shape. This technique is referred as breakaways [KTP10]. The cones are placed in the center of each tumor which can be calculated by taking the average of its minimum and maximum x , y and z coordinates. The size/opening for each cut volume is user defined although the smallest possible size should at least contain the whole tumor. To make sure that the cut volumes contain all the structures that lay in them each cone has to be extended. Knowing that the 3D models cannot extend arbitrarily due to the designated shape of the liver, it is sufficient to scale the cones until they almost reach the near plane. However,

when the cones are close to one another, they will inevitably overlap and will block the view to the cut volumes. In order to force the overlapping faces not to be rendered when using OpenGL, a depth test of `GL_GREATER` should be used during the rendering phase of the cones. However, there are cases where the depth test of `GL_GREATER` will not have any effect, for example when only one cut volume is visualized or if the cut volumes are too far to overlap and thus will block the view to the rest of the scene. In order to size the cut volumes accordingly, the surface of the 3D liver model is used to set their borders. A depth test of `GL_GREATER` should be performed when rendering the cut volumes and the liver's surface which will lead to only rendering the sized cut volumes. Thus, the cut volumes are adjusted properly and block as less as possible from the structures that do not lay in them as seen in Figure 3.

4. Results

The final step would be to visualize the cut volumes and the structures that lay in them according to Section 3.3 and the rest of the scene according to Section 3.1 and Section 3.2. Moreover, the cut volumes' color should be as close as possible to the actual liver's color in order to create a more even result. However, the live endoscope image has a lot of different gradients due to the liver's structure, the specular light from the endoscope's light source and of course areas that are not lit properly. Testing a lot of different approaches to color the cut volumes has led to the conclusion that it is sufficient to sample the color of any pixel that approaches the main color gamut of the liver. The final composition can change according to our preferences. We can visualize all the cut volumes at the same view, isolate a cut volume at a time, change the size of all or specific cut volumes and finally add some transparency on them to be able to track the structures

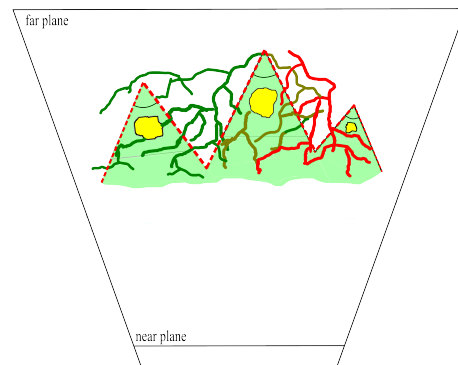


Figure 3: Simulation of the properly sized cut volumes marked in red strip lines. The green contour shows the liver's surface that was used to size the right most and left most faces. The two middle overlapping faces were removed when rendering only the cones with a depth test of `GL_GREATER`.

that lay behind them. Figure 4 shows a composition when all the cut volumes are visualized with different sizes and a low transparency level.

Additionally, the developed implementation can be applied to the 3D liver's surface instead of the live endoscope image. In Figure 5 one cut volume is visualized with a semi-transparent surface.

5. Conclusions

Modern systems are capable of overlaying the pre-operatively extracted 3D models of the patient's liver inner structures, onto the live endoscope video stream during a laparoscopic liver surgery. However, by simply overlaying the 3D models on the live endoscope's video stream is not sufficient to provide a highly accurate spatial and depth perception. Thus, a cone is placed on the position of each tumor facing the camera. Due to the cone's angular shape it is easier to rate the depth of the cut and the distances between the intersected structures. The 3D models that do not lay inside any of the cut volumes are passed through an edge-detection algorithm and blended with the live endoscope image. In that way they still preserve and depict their spatial relation with the rest of the structures. Future considerations in order to achieve a better result would be to add shadows and/or distance lines in the form of rings across each cone's surface.

Acknowledgements

The presented concepts have been developed and evaluated in the Inviwo framework (www.inviwo.org), and have been interfaced with the CAScination navigation system and an augmented reality framework developed at the ARTORG Center for Computer-Aided Surgery.

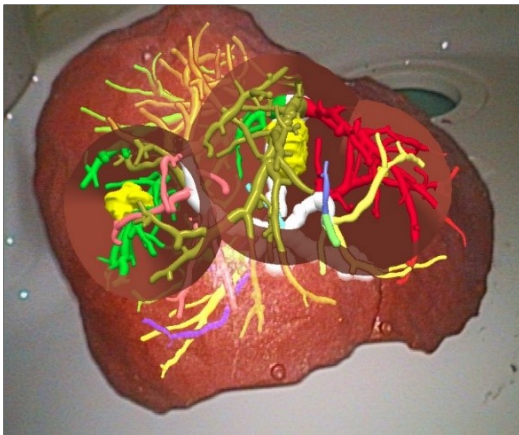


Figure 4: Visualization of all the cut volumes set with different sizes to give a better spatial understanding of the structures. The cut volumes have been set semi-transparent to track the structures that lay behind them.

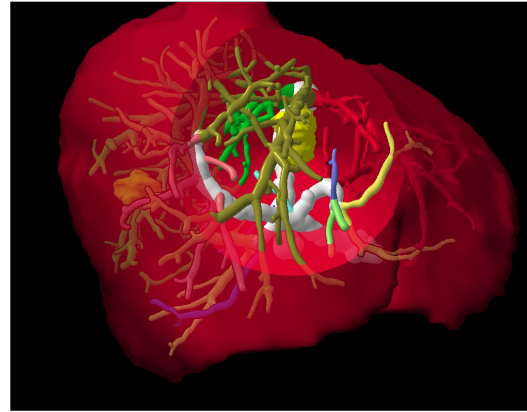


Figure 5: The proposed technique using the 3D model of the liver instead of the endoscope image, isolating one cut volume. Transparency is used for both the cut volume and the liver's surface.

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