Computer Aided Liver Surgery Planning: An Augmented Reality Approach

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ABSTRACT

Surgical resection of liver tumors requires a detailed three-dimensional understanding of a complex arrangement of vasculature, liver segments and tumors inside the liver. In most cases, surgeons need to develop this understanding by looking at sequences of axial images from modalities like X-ray computed tomography. A system for liver surgery planning is reported that enables physicians to visualize and refine segmented input liver data sets, as well as to simulate and evaluate different resections plans. The system supports surgeons in finding the optimal treatment strategy for each patient and eases the data preparation process. The use of augmented reality contributes to a user-friendly design and simplifies complex interaction with 3D objects. The main function blocks developed so far are: basic augmented reality environment, user interface, rendering, surface reconstruction from segmented volume data sets, surface manipulation and quantitative measurement toolkit. The flexible design allows to add functionality via plug-ins. First practical evaluation steps have shown a good acceptance. Evaluation of the system is ongoing and future feedback from surgeons will be collected and used for design refinements.

Keywords: Liver surgery planning, augmented reality, segmentation revision, deformable models, voxelization

1. INTRODUCTION

Planning of surgical liver tumor resections based on tomographic imaging modalities like X-ray computed tomography (CT) is a complex task, involving the identification of structures of interest (liver, vasculature, liver segments and tumors), followed by an assessment of the three-dimensional (3D) relationships between these objects. The decision if a resection is suitable or not and the detailed strategy for the surgical intervention is mainly based in the outcome of this assessment. A crucial step during the planning stage is the process of developing a 3D understanding of the complex structures based on cross-sectional images. This step usually requires joint efforts from radiologists and surgeons.

By building a virtual liver surgery planning system this process can be facilitated as shown in recent publications.[1–3] The main challenge for radiologists is the segmentation of liver, vasculature and tumors, as well as liver segment estimation, in order to provide all the information needed for surgical planning. This process is tedious and time consuming if done manually. On the other hand fully automated segmentation approaches will fail in some cases due to the large variability of shape and gray-value appearance of normal or diseased objects to segment (e.g. liver cirrhosis in the case of liver segmentation). The challenges radiologists face are interaction with 3D objects for viewing, specifying tissue subject to resection or taking distance measurements. 3D interaction is also an important key for building a 3D understanding of complex objects and their relations.

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The developed augmented reality (AR) based liver surgery planning system supports both, radiologists and surgeons during the planning stage. It can be seen as an interface between radiologists and surgeons with a well defined information flow. The intentions concerning augmented reality were the following: Current computer aided liver surgery planning applications are conventional desktop systems. The interaction with virtual objects on the desktop is not very intuitive, especially for untrained surgeons. Additional time needed for training raises the acceptance threshold of the system. Adding stereo capable display devices makes topological structures more understandable, but the interaction remains the same. Input devices with only two degrees of freedom (DOF) are used for 3D space interaction tasks, which ideally involve six DOF (three for position and three for orientation). Special input devices such as trackballs provide six DOF for interaction, but they are also quite cumbersome, because interaction is done indirectly. Besides the interaction deficiency, a desktop surgery planning is not very sociable in terms of collaboration.

The developed system is a visually coupled AR system, thus a system using head tracking for correct stereoscopic visualization. Surgeons and/or radiologists wear see-through head mounted displays (HMDs) that display virtual objects e.g. the liver surface, vessels and tumors, while the surrounding world can still be seen and interacted with. Virtual objects can be observed as if they were real. Surgeons may walk around, have a closer look and move the objects directly for instance. A natural way of interaction with virtual objects is provided due to the use of tracked input devices. The capabilities of the AR environment are utilized throughout the system (e.g., for 3D segmentation result inspection and editing, as can be seen in Figure 1). User interaction is limited to cases where automated algorithms fail and the amount of time required by radiologists for fixing a segmentation problem can be lessened compared to using a manual approach. An expansion of the developed core system for intra-operative applications is possible and provides the advantage of having one platform for planning and support during surgery. The system is also suitable for other uses in the medical field including telemedicine applications.

2. RELATED WORK

2.1. Computer Assisted Liver Surgery Planning

There have been quite a number of approaches towards computer aided liver surgery planning. Most of them focus on segmentation and desktop based planning, while visualization and interaction are of ancillary importance. *Cardenas et al.*[1] introduced a desktop liver operation planning system, providing tools to segment the liver, tumors and the vascular structure based on CT images. The extracted structures may also be visualized in a three-dimensional fashion. Another system destined for minimally invasive liver surgery was developed at *INRIA, France*.[2] It involves segmentation of the liver and interior structures based on deformable surfaces.[4] The same group also incorporated physical liver tissue properties into their simulations and used force feedback for interaction tasks.[5] Even though Virtual Reality (VR) techniques such as force feedback devices are used, visualization is desktop based. Work in the field of virtual surgery planning has been carried out by the German Center for Medical Diagnostic Systems and Visualization (*MeVis*).[3] The system developed there features segmentation modules, desktop 3D visualization and fully automatic calculation of resection proposals. Most of the efforts have been put on segmentation and higher level tasks such as skeletonization and liver segment approximation. From the visualization point of view the system features both volume and surface rendering on the desktop.

2.2. Augmented Reality

While there are many research projects in the field of computer aided surgery, up to now only few of them employed AR techniques. However, surgery planning using AR techniques is an emerging research field. There have been efforts to bring augmented reality to laparoscopy at the University of North Carolina (UNC) by *Fuchs et al.*.[6] They used a see-through head mounted display to explore multiple laparoscopic imaging data sets acquired in a preprocessing step, which widens the field of view for the surgeon and reduces the need to move the laparoscopic camera. *Edwards et al.*[7] proposed an AR system coupled with a surgical microscope. As in the UNC system, preoperatively taken images are overlaid with real world images in the microscope. Both systems suffer from inaccurate registration.[6,7] *Salb et al.*[8] are also driven by the idea of superimposition of the actual patient's view with virtual surgery planning data represented as surface- or volumetric models using see-through

HMDs. *Fuhrmann et al.*[9] developed an intraoperative liver surgery system named *ARAS* (Augmented Reality Aided Surgery). The goal of the *ARAS* project is to aid surgeons during the liver resection by visualizing CT data and intraoperative ultrasonic (US) data in 3D by means of direct volume rendering techniques together with the portal vessel tree. Wearing optically tracked HMDs, and using tracked 3D input devices surgeons are able to interact with the system. The idea behind this system is that the surgeon wears the HMD while the operation takes place, in order to see the vascular tree aligned to intraoperative ultrasound images. *Schorr et al.*[10] present a surgery planning system for both pre- and intraoperative use which provides a generic interface for different input devices and visualizations. Another system using augmented reality techniques for intraoperative navigation was developed at Center of Research in Micorengineering *CRIM*, Italy.[11] Augmented reality visualization techniques are used for displaying the spatial relation between the surgical tools in echographic guided biopsy, to support the procedure. There have also been attempts to use AR techniques for computer aided surgery at AKH Vienna, Austria.[12]

3. SYSTEM OVERVIEW

The following section gives an overview of the developed system concerning both, the possible application modes of the system and the hardware setup used. In this paper we focus on the tasks of quality assessment and editing of structures retrieved from a preceding segmentation step and on the actual resection planning procedure (see Figure 1). This work is part of a superior project that involves the image processing tasks necessary for computer aided liver surgery planning as well. Section 3.1 focuses on the system from the users' point of view. Different ways of interaction are described in detail based on the overall workflow. Details on the hardware setup used can be found in Section 3.2.

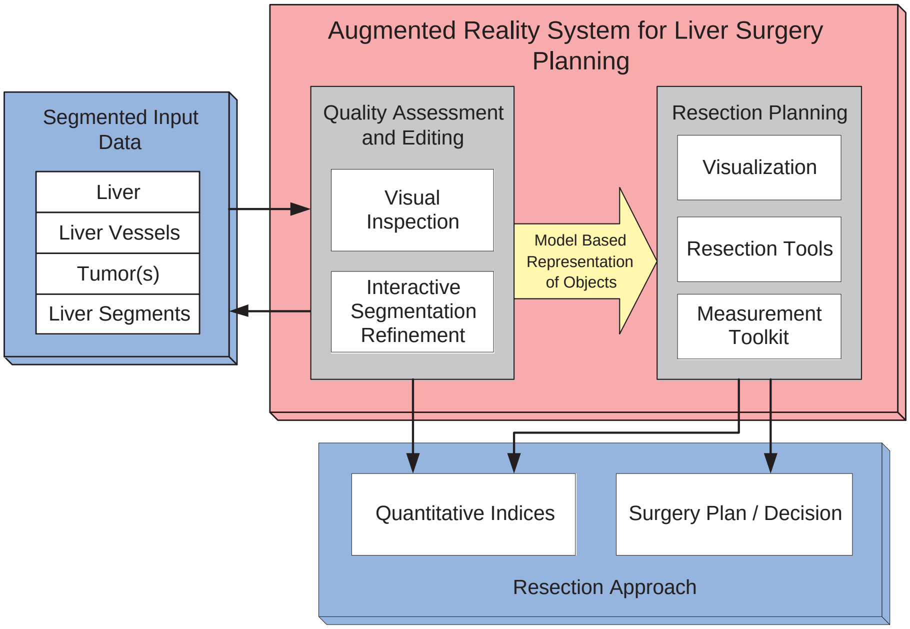

Figure 1. Overview of the developed system. Quality assessment and editing of segmentation results, on the one hand and resection planning on the other are the main objectives.

3.1. System Operation

The proposed system uses automatically segmented CT datasets as input data. Any segmentation technique either manual, semiautomatic or fully automatic, can be applied to obtain an initial segmentation. However, robust techniques are preferred. Qualified segmentation techniques for different subproblems in the context of liver surgery planning were, for example, recently introduced by *Soler et al.*[4] and *Beichel et al.*.[13]

Visual Inspection

Once the initial segmentation is available, the radiologist may load the datasets into the AR environment for visual exploration and evaluation. To do so, the segmented objects are converted to surface representations using surface reconstruction techniques described in more detail in Section 4.1. Surface reconstruction is done for the most important structures only, while context information is displayed using direct volume rendering (see Section 4.4). The radiologist may observe the organ from different viewpoints and distances by walking around it or directly moving it using the tracked input devices. In addition the transparency of the objects can be altered in order to make topological relations more understandable. The ability to move a tracked panel showing original CT data through the scan volume is another key feature. It opens up a highly intuitive way for visual evaluation of the input segmentation based on the surface models reconstructed from them. Clipping the object slightly above the tracked panel, which is also possible, allows for more accurate evaluation at object boundaries.

Interactive Segmentation Refinement

The task of interactive segmentation refinement is closely related to the visual inspection. Instead of just evaluating the segmentation, interaction with tracked input devices is used to manipulate the surface representation of the segmented objects. The developed liver surgery planning system provides various tools for interactive true 3D editing of the surface representation ranging from generic, mesh based methods to others taking higher level shape information into account. The results of single deformation steps can be visualized throughout the editing process moving the CT data textured panel to locations of interest. It is moreover possible to place snapshots of arbitrarily oriented planes cutting through the liver tissue in space, to keep in track of outcome of surface edition. The deformed surface representations of e.g. the liver surface may be exported to traditional volume datasets at any time using fast voxelization techniques described Section 4.5. The interactive use of these tools enables radiologists to correct imperfect segmentations intuitively, requiring only little amounts of time.

Resection Planning

Once the accuracy of all reconstructed liver structures has been approved by the radiologist, resection planning by the surgeon can be performed using the same tools. In case the two physicians wear HMDs they can explore the datasets in a collaborative way. In addition, measurements tools are provided to quantify e.g. the total liver volume, the volume of individual liver segments or tumors. Distance measurements from arbitrary points in space to specific objects are realized by other tools within the system as well as visualization of security margins around tumors. These tools enable surgeons to decide whether it makes sense for the patient to undergo a resection or not. In case a resection is indicated, a resection plan may be elaborated based on information gained from the visualization.

3.2. Hardware Setup

The proposed hardware setup consists of the following components:

- Stereoscopic see-through HMDs (Alternatively a stereoscopic large screen projection system can be used)
- Tracking System
- Tracked Input Devices
- Rendering Workstation(s)
- Tracking Workstation

Visualization of virtual objects is done using a see-through capable head-mounted display. For clinical use, a lightweight high-resolution HMD providing a wide field of view is preferable. Beside using HMDs the system has successfully been tested using a stereoscopic large screen projection system (151 inch screen). The visual quality is still satisfying, however, correct stereoscopic visualization for multiple users is impossible using the projection setup. In order to be able to see and interact with the real world, the projection system should be sufficiently bright to allow for daylight use.

The tracking system delivers position and orientation data of the users' heads and input devices. An optical tracking system is used, which outperforms commonly used magnetic systems in terms of accuracy and sensitivity to distortions. The use of four cameras is sufficient in order to avoid occlusion problems. In addition, optical tracking makes cumbrous cables obsolete. The overall performance of the system highly depends on the accuracy of the tracking system and the calibration of the system. Our input devices are those proposed for the *Studierstube*[14] AR environment: A tracked pencil *PEN* and a transparent plexiglass personal interaction panel (*PIP*). Both input devices are tracked delivering six DOF tracking data approximately 60 times per second. The pen is equipped with buttons, to trigger input events. Computing hardware consists of dual processor active-stereo capable rendering workstations (AR controllers), one per user, to render virtual objects. Tracking data are sent across a local area network from a tracking workstation to the AR controllers. Figure 2 gives an overview of the hardware setup used. The equipment can be integrated into surgical environments without major efforts, as facilities to mount tracking cameras or HMD signal cables are normally available in rooms used for surgery planning.

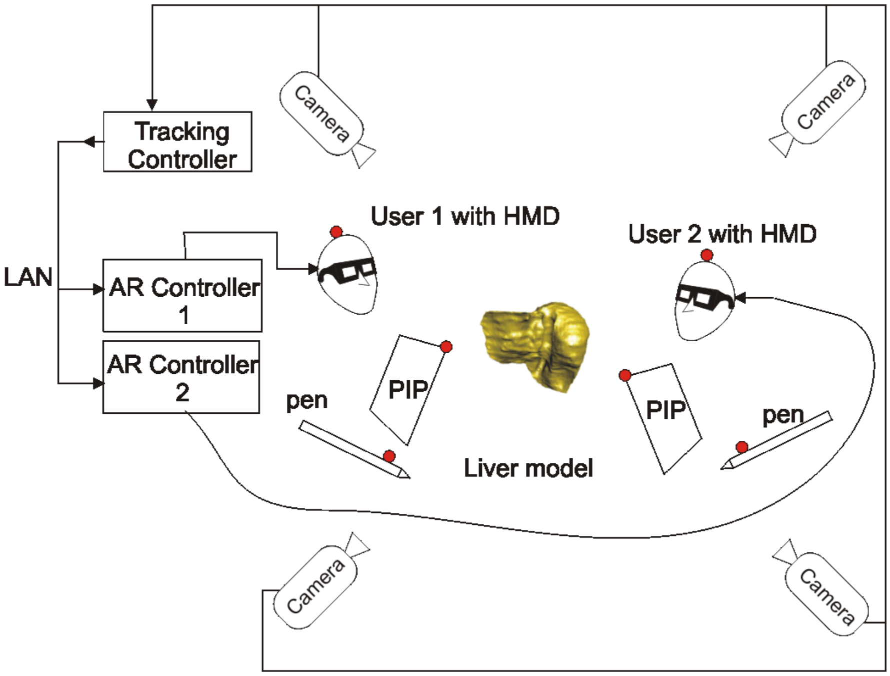

Figure 2. Augmented reality setup consisting of an optical tracking system, one or more HMDs driven by AR controllers, tracked personal interaction panels (PIPs) and tracked pointing devices (PENs). Multiple users can view an interact with the virtual liver model, while the surrounding real world environment is still visible.

4. APPLIED METHODS

Figure 3 illustrates the relation between the application modes described in Section 3 and the applied methods. In this section the methods developed or applied to solve sub-problems in the context of computer assisted liver surgery planning are described in more detail.

4.1. Surface Reconstruction

Surface representations are used for visualization most of the time, throughout the project. They are reconstructed from the segmented volumetric CT datasets using a method introduced by *Guèziec et al.*[15] named the *Wrapper* algorithm, which is itself based on the marching cubes algorithm published by *Lorensen et al.*.[16] The main advantage of the wrapper algorithm is, that, in contrast to the conventional marching cubes algorithm, it always delivers meshes without cracks.

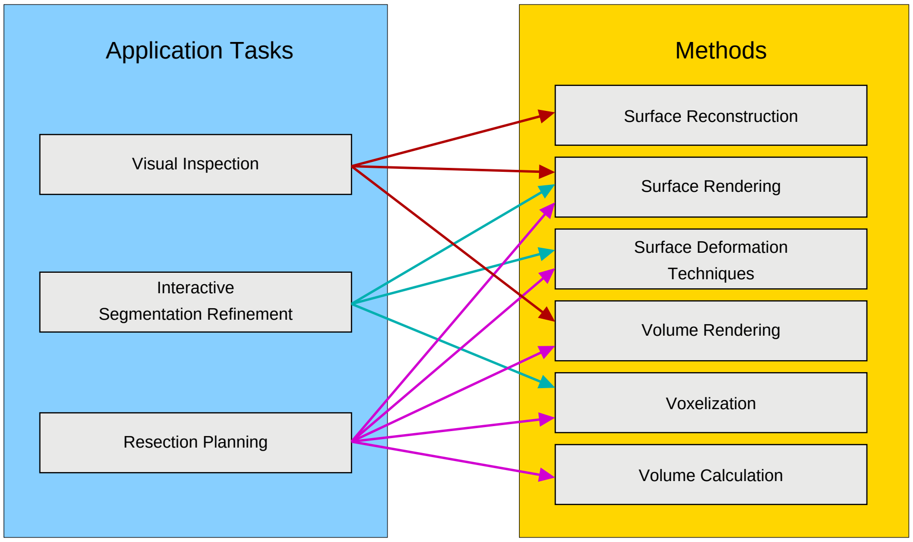

Figure 3. Main application modes/tasks and the methods applied in each of the tasks - the linkage is quite tight.

4.2. Deformable Surface Models

In order to refine and correct the initial (automatic) segmentations, deformable surface models are employed. In an AR framework deformations have to be very time efficient in order to allow real-time interaction. On the other hand the surface representation subject to deformations must be accurate, thus geometrically complex. As a consequence of the two goals, interactivity and accuracy, techniques like finite elements cannot be considered. The need for real-time rendering prohibits expensive conversion of data to formats suitable for rendering on graphics hardware, which favors triangular meshes. Unfortunately the varying neighborhood in terms of the number of edges each vertex belongs to complicates deformation calculations.

Simplex meshes, as proposed by *Delingette et al.*,[17, 18] which can easily be constructed from triangular meshes, provide an easy to use framework for deformations. They are the *dual* data structure to triangular meshes. The deformable character of the simplex mesh is achieved by setting up a force framework on top of the mesh structure. Forces are calculated for each simplex separately, based on the location of the simplex. There are two types of forces: internal and external ones. Internal forces regularize the mesh locally. They are based on the position of the simplex relative to its neighbors and exhibit, up to a certain extent, pseudo-physical properties of the mesh. External forces are employed to pull the mesh vertices towards attractors of different kinds. Damping factors prevent the mesh from degeneration. The effect of smooth deformation is achieved by applying displacements based on the accumulated forces to all of the simplexes iteratively.

Our liver surgery planning system uses deformable simplex meshes for mainly two tasks:

- **Surface Reconstruction** - Simplex meshes are used to reconstruct the surfaces of given segmentations. They are employed using the outcome of the wrapper algorithm introduced in Section 4.1 as input data. Using simplex meshes an initial mesh can be reconstructed from a coarse segmentation resulting in a small mesh. Conversion to a simplex mesh and iterative deformation based on forces towards the segmentation boundary results in a smooth surface representation for both the liver surface and all interior and pathologic objects. The low mesh complexity, achieved without explicit mesh simplification is suitable for real-time rendering.
- **Segmentation Refinement** - User interaction can be formulated as external force in the simplex mesh framework. The model is highly adaptable, enabling a wide range of segmentation refinement tools described in Section 4.3.

4.3. Segmentation Refinement

Refinement of erroneous segmentation results produced by (automatic) segmentation techniques is a central part of the system. Augmented reality together with deformable surface models provide a very powerful framework for this task. In contrast to desktop based systems, where user interaction is restricted to 2D input devices such as a 2D mouse, tracked VR/AR input devices enable direct and in-place user interaction. Efficient segmentation refinement and mesh editing demands for direct interaction to ensure a small amount spent on interaction.

The main problems resulting from automatic segmentation of the liver surface are outliers resulting from surrounding tissue of approximately the same Hounsfield Units (HU) in the CT scan. On the other hand tumors close to the liver surface result in concave holes in the mesh.

Up to now we address these problems by providing a number of segmentation refinement tools for

- Freeform Deformations
- Shape Related Local Deformations
- Attractor Point Deformation

Work on additional tools is in progress.

All these tools benefit from the stereoscopic visualization and from the use of tracked true 3D interaction. In the case of segmentation refinement, the backside of the personal interaction panel is used to display arbitrary cutting planes through the liver and its surrounding regions, textured with the original CT scan data. This allows for visual verification of the current segmentation at any time throughout the segmentation refinement process. The implementation is based on 3D OpenGL textures.

Freeform Deformations

The developed freeform deformation tools allow for displacement of the simplex mesh vertices within a spherical influence area using AR input devices. The center of the influence area is specified using the tracked pen, while the size of the influence area can be modified using 3D equivalents of well known 2D widgets on the PIP before the deformation. The deformation itself is initiated by pressing a button on the pen. Once this happens, influenced mesh points are located using a nearest neighbor search based on the well known kd-tree data structure followed by a breadth-first-search operation on the mesh surface. The actual mesh vertices are displaced using a suitable influence function around the center of influence. Moving the pen while the button is pressed results in temporary deformation, releasing the button finally modifies the mesh. The freeform deformation tool does not use the mesh immanent force framework.

The freeform deformation tool is the most generic one. It enables for deformation on a fine grained level with the maximum number of DOF. On the other hand this can easily lead to unexpected behavior or mesh degeneration like unnatural bumps, if not used carefully. Therefore it should mainly be used for final refinements.

Shape Related Local Deformations

Besides freeform deformation the developed systems provides shape related deformation tools. In contrast to freeform deformation, this deformation tool takes local surface properties like the normal vector and the curvature, into account. The user may specify a point the segmented surface should attract to. The forces towards the temporary attractor point are calculated using the simplex mesh force framework, in a single or multiple iteration steps. Force calculation takes into account mesh internal forces, and if applicable, forces towards the attractor point. These forces are weighted based on the distance to the attractor and the distance from the mesh vertex closest to the attractor. The shape related deformation tool is mainly motivated by the need to deform the mesh surface without modification of the overall shape, e.g., the automatic segmentation missed the tip of the left liver lobe. In this case bump-like deformations are not desirable.

Attractor Point Deformation

The third segmentation editing technique introduced is deformation based on attractor points. It is conducted by the idea to specify a small number of attractor points. These points define fixed points for the simplex mesh, points the surface representation must touch. Integration of such attractor points into the simplex mesh framework happens seamlessly. Conventional external forces are replaced by forces towards these attractors. Unwanted mesh deformation is avoided by specifying hot and cool regions of the surface representation. Cool regions ignore the attractor points, while there is more impact in hot regions. Hot and cool regions themselves are specified by painting the surface object to deformations using the PEN as a paint-brush.

Attractor point based deformation proved to be helpful in cases the automatic segmentation was adversely influenced, e.g., by pathologic tissue near the liver boundary. In such cases the liver surface representation may contain concave holes, which can be removed using this technique.

4.4. Volume Rendering

Besides surface representation which displays the liver, vasculature, liver segments and tumors, direct volume rendering is provided to enrich these objects with context information. This should enable surgeons to validate the segmentation refinement and to get a feeling of relationships with other structures.

Recently, volume rendering techniques got much attention in computer graphics demanding interactive frame rates. The newest graphics hardware features are exploited to provide good results interactively.[19] Unlike traditional software-based approaches like ray casting,[20] the Shear-Warp algorithm,[21] or Fourier volume rendering,[22, 23] these hardware-based methods use the texture memory of the graphics card to render the volume. A detailed description of these techniques can be found in.[19, 24] The presented system adopted some of these ideas to get a volume visualization which provides context information and enriches the surface representations explained above .

The crucial point in AR visualization is to provide an intuitive user interface easily understandable by non-expert users. Especially for volume rendering an easy-to-use transfer-function modification mechanism must be found to enable interactive color and opacity assignment to the volume. Therefore, the transfer function is mapped onto a 2D plane visible on the PIP. By using the pen, physicians can set independently red, green, blue, and alpha channels for different intensity values of the volume as illustrated in Figure 4(b).

4.5. Voxelization and Volume Calculation

Another important aspect of liver surgery planning is the ability to measure volumes. Surgeons desire to get a steady feedback of the objects' volume. In case of segmentation refinement and segment resection, the surface can be modified by the user arbitrarily. Hence, the volume of each surface model changes all the time.

An efficient way of calculating one's volume is to perform a voxelization on the surface model. Voxelization can be described as the process of approximating a continuous surfaced-based model by some discrete voxel space. Different techniques have been proposed in literature focusing on either efficiency[25] or robustness.[26]

The speed of voxelization closely corresponds to the required resolution. Nowadays, typical resolutions are 256×256×256 or 512×512×512 which are sufficient for a wide range of applications. However, the demand for higher resolutions is driven by bigger and more complex models for which traditional software-based methods[27, 28] are too slow. Hence, several novel approaches have recently been proposed for hardware-accelerated voxelization algorithms. In this domain, we have implemented an efficient algorithm which allows interactive voxelization response times (results can be observed in Section 5).

After the voxelization is performed, the volume can be calculated by summing up all voxels and multiply them by their volume. A special data structure can handle different voxel classifications liver, vasculature, tumor and segments can be easily distinguished.

5. RESULTS

Currently, all methods presented above have been implemented in our liver surgery planning system. Figure 4(a) demonstrates how a liver rendering can be studied in a collaborative way. The PIP textured with cross-sectional CT image data can be moved through the virtual liver volume, while the virtual liver model is clipped slightly above the PIP. This makes it easy for the radiologists to visually verify the correctness of the liver boundary. In Figure 4(b), the surface representation is enriched by a volume visualization of the original dataset. The brightness transfer function can directly be drawn on the PIP to assist the visualization. The current implementation allows frame rates of about 10 frames/sec for a stereoscopic projection. According to surgeons', these frame rates are acceptable. The task of free-form segmentation refinement is illustrated in Figure 4(c). Another feature of our system is presented in Figure 5. It shows snapshots taken using the PIP as plane specification device.

The ability to provide interactive volumetric measurements is demonstrated in Table 1. The interactive character facilitates that, for instance, the liver volume can be provided in 604 millisecond intervals (for a resolution of 256×256×96). This feature enables surgeons to interactively plan the surgery and calculate the resection index very quickly. Table 1 shows different voxelization results of liver, vessels, and tumor including the response times and calculated volumes. While the number of compared measurements will be increased in the future validation studies, these first result demonstrate promising reproducibility of volumetric measurments for different voxelization schemes.

Object	**Resolution**	**Time (msec)**	**Voxelized Volume** dm^3
Liver	256x256x96	604	1.3214
	512x512x192	2112	1.3224
Vessels	256x256x96	1671	0.02796
	512x512x192	3740	0.02854
Tumor	256x256x96	230	0.06455
	512x512x192	810	0.06472

Table 1. Voxelization results for liver, vessels, and tumor in one subject.

Not all of the methods presented in this paper have already been extensively evaluated by physicians. However, first test sequences have been initiated to study their usability and more complex evaluation is underway.

6. DISCUSSION AND CONCLUSION

The whole system developed so far represents a new approach for virtual liver surgery planning. A new technique to revise segmentation results globally or locally in 3D utilizing the augmented reality environment was developed. The core functionality needed for virtual resection planning including suitable visualization techniques, interaction methods for the definition of resections as well as quantitative assessment tools for the virtual surgery in terms of (liver) volume calculations have been developed. The extension of the core functionality via plug-ins is ongoing. By using feedback from physicians, the system will be improved further with special emphasis on the user interface design. The input data segmentation process is also aided. First practical evaluation results are promising and full scale evaluation is underway.

The outlined AR based virtual surgery planning system poses an excellent tool for surgical planning, due to stereoscopic 3D visualization and the intuitive navigation. It may become a basis for many other applications in the area of computer aided surgical planning and intervention.

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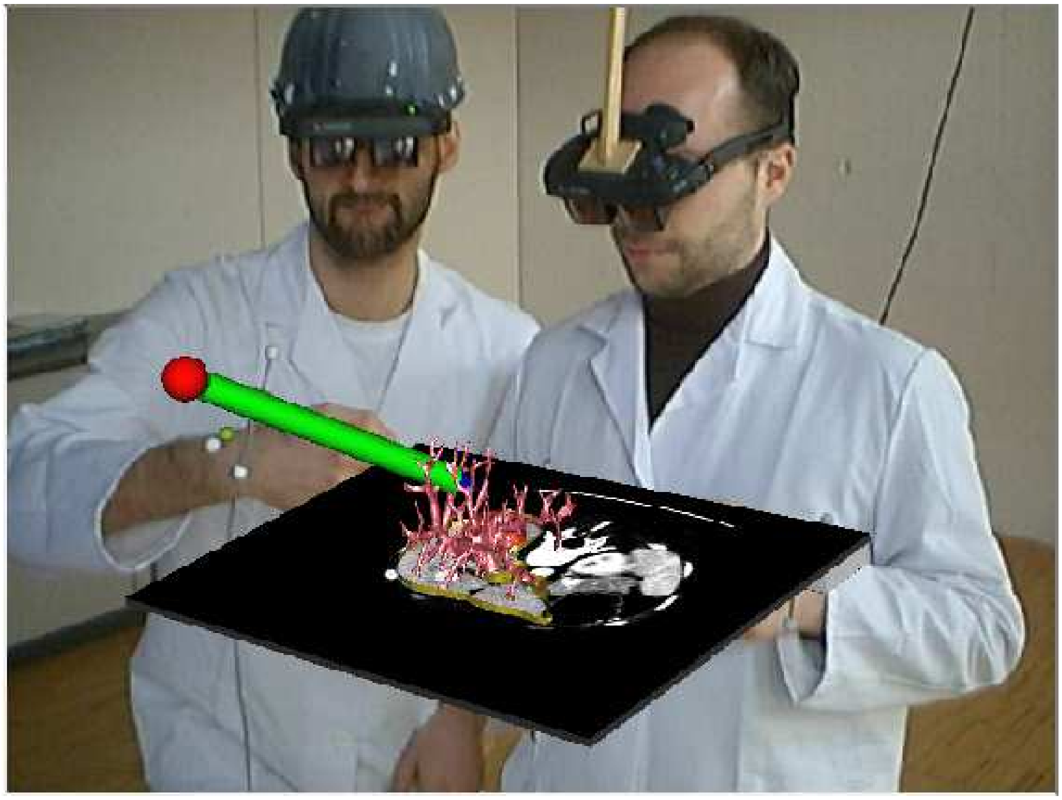
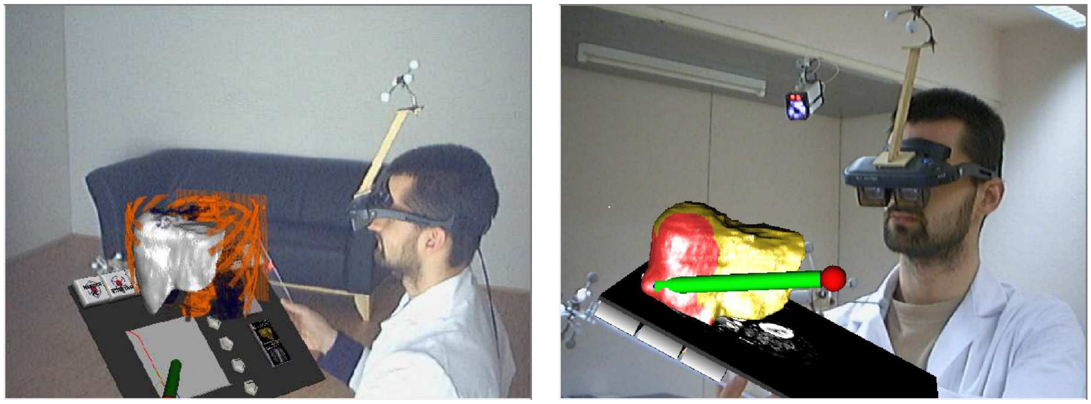


(a) Collaborative liver surgery planning



(b) Volume Rendering - The transfer function can directly be drawn onto the personal interaction panel (PIP).

(c) Segmentation Refinement - The liver surface can be revised using the PEN. The PIP is used to visually evaluate the result.

Figure 4. Liver surgery planning in an AR environment at a glance.

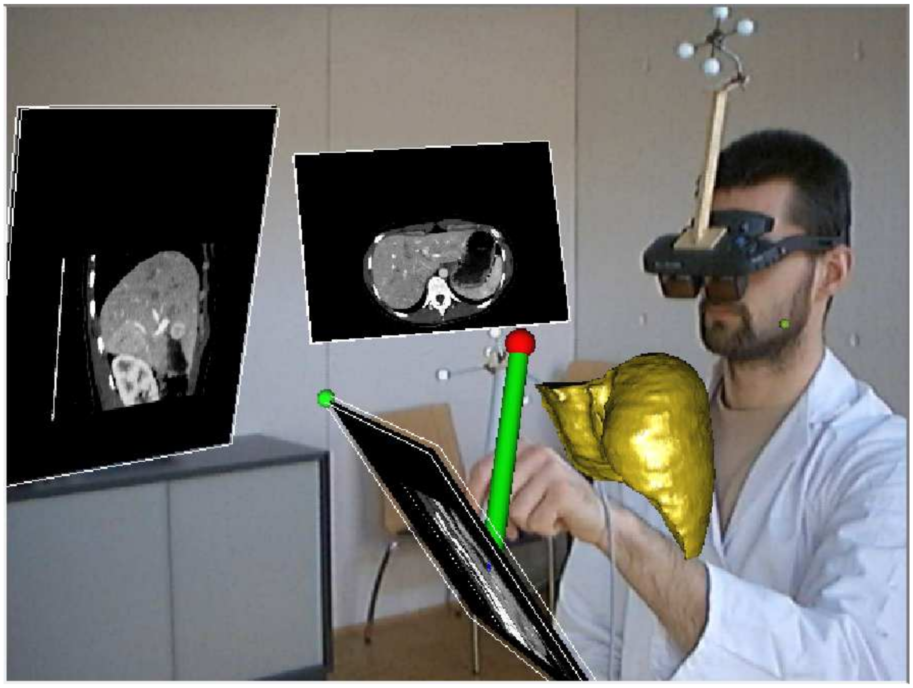


Figure 5. CT snapshots positioned within the AR environment

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