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A Hybrid User Interface for Manipulation of Volumetric Medical Data

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ABSTRACT

This paper presents a novel system for interactive visualization and manipulation of medical datasets for surgery planning based on a hybrid VR / Tablet PC user interface. The goal of the system is to facilitate efficient visual inspection and correction of surface models generated by automated segmentation algorithms based on x-ray computed tomography scans, needed for planning surgical resections of liver tumors. Factors like the quality of the visualization, nature of the dataset and interaction efficiency strongly influence system design decisions, in particular the design of the user interface, input devices and interaction techniques, leading to a hybrid setup. Finally, a user study is presented, which characterizes the system in terms of method efficiency and usability.

CR Categories: C.2.4 [Computer-Communication Networks]: Distributed Systems—Distributed Applications; I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling—Boundary Representations; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual Reality; J.3.2 [Medical information systems]: Project and People Management—Life Cycle

1 INTRODUCTION

Imaging modalities like X-ray computed tomography (CT) or magnetic resonance tomography (MR) are important information sources for surgical planning. Proper planning requires physicians to understand the 3D relations within the dataset. For example, the resection of liver tumor requires understanding the arrangement of liver tissue, vasculature and tumor. Looking at individual 2D slices of CT data using conventional radiological workstation software makes this task difficult. Our aim was therefore to build a system for liver surgery planning using Virtual Reality (VR) techniques, capable of supporting radiologists and surgeons by providing visualization of 3D medical models and tools for computer-assisted planning of the surgical intervention.

Typically, the first step in liver surgery planning is segmentation of the individual structures, needed to plan the surgical intervention. This task can be done manually, but this is tedious and time consuming, since it involves drawing contours on several hundred slices.

However, a fully automated segmentation of the liver is difficult to achieve, because the shape of the human liver highly varies. This fact makes it almost impossible to use a priori shape knowledge for the design of a segmentation algorithm. In addition, the gray-value appearance can show large variations due to pathological changes of the liver, which can cause problems in distinguishing the liver from adjacent organs with similar gray-values (e.g. heart or colon). Furthermore, tumors located close to the liver boundary might be excluded from the segmentation.

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In advanced automatic segmentation algorithms, the segmentation problems are usually limited to local errors, while most areas of the liver boundary can be correctly found using the automatic algorithms. A radiologist's task can therefore be simplified from manual contour specification to interactively correcting errors in segmented datasets. This *segmentation refinement* approach is expected to be much less time consuming in most cases.

At a first glance 3D segmentation refinement tools afford VR techniques: Stereoscopic visualization provides good 3D perception of the dataset, whereas tracked input devices allow for direct 3D interaction with the dataset. However, 2D screens have a much higher resolution than their 3D counterparts, and an inexpensive optical mouse easily outperforms high-end tracking devices in terms of accuracy when precision input in 2D is required. In the medical field, where imprecision may have dire consequences, the virtues of established 2D techniques should not be discarded lightly. Moreover, physicians are used to desktop interfaces, and in particular for system control, VR interfaces are not yet mature.

These considerations lead us to the design of a hybrid user interface that combines multiple display and interaction techniques, in order to match the work processes at hand. The objective of the hybrid user interface is to pair 3D perception and direct 3D interaction with 2D system control and precise 2D interaction. For such an interface, it is important that the flow of action of working between 2D and 3D visualization and interaction techniques is not disturbed. Both the different views and the interaction with the data need to be handled coherently.

To ease the transition between the interface modalities, a hybrid input device, which can be conveniently used in all 2D and 3D tasks, was designed and developed. A focus was put on analyzing the differences between action performance in the 2D and 3D domain, leading to a more extensive human factors study. This paper presents results on the complexity of tasks and their associated tools, and the duration of usage in reflection to ergonomics.

2 RELATED WORK

The three-dimensional nature of surgery planning and surgery simulation has led researchers to the use of VR techniques. An overview of VR systems and human interface issues in the medical context can be found in [21] and [9]. Liver surgery planning in particular has been addressed by a number of groups, although VR aspects are rudimentary in most projects.

The German cancer research center (DKFZ) located in Heidelberg has developed a computer-aided planning system for liver surgery [20]. Research was focused on medical image processing tasks such as segmentation. There have also been attempts to deal with segmentation errors described in [16], although the VR aspects of the system are limited, since all image segmentation and planning procedures are performed on a normal desktop PC.

The Center for Medical Diagnostic Systems and Visualization (MeVis) in Bremen has developed a desktop-based liver surgery planning system. The main research focus was segmentation and modeling of liver structures [15].

Researchers at INRIA have addressing several aspects of liver surgery planning, such as the segmentation of the liver surface using

deformable surface models. Later the group worked on surgical simulation with realistic liver tissue models using force feedback input devices [8]. The virtual liver surgery planning system [3], which is the foundation of the work presented in this paper, has been developed at Graz University of Technology since 2000. An earlier version of the VR based segmentation refinement toolset was described in [4].

Segmentation refinement is a rather new field and there are hardly any publications dealing directly with it. 2D segmentation can be trivially implemented as a painting tool, but this approach is ineffective for large 3D datasets. Interactive segmentation techniques can be seen as closely related, although they address the segmentation problem and not the correction of erroneous segmentation. An interactive segmentation approach named *Live-Wire* was introduced in [1]. It reduces the amount of user interaction required to segment the object boundary. An extension to 3D data can be found in [10]. To our knowledge, the desktop based interactive approach described in [19] is the only method based on the segmentation refinement principle. An application in the context of data preparation for liver surgery was reported in [2].

3D interaction with medical volumetric datasets is a reoccurring topic in VR. Some input devices have been developed that specifically focus at exploring medical data, including Hinckley's prop-based system [18] or the Fakespace CubicMouse [13].

Hybrid user interfaces in general are an emerging research field [11]. Most developments focus at combining different visual displays, like in mixed reality setups [23]. Only a few have focused at truly hybrid input, such as the Virtual Tricorder [27], the Pick-and-Drop approach by Rekimoto [22], and some tangible user interfaces [26]. Handhelds and touch screens have been integrated into immersive environments for interaction purposes, like [12], [27], [14] and [6]. These handhelds are mostly used for GUI-style control elements (system control), only little work is done on direct manipulation of immersive data. Similar to handhelds, tablet interfaces have been designed for the display of 2D data and menus on a flat surface, for example [25]. Finally, a frequent approach to system control in immersive environments are pen-like devices, such as the Stylus products from Polhemus or Intersense. For an extensive overview of pen devices, please refer to [5].
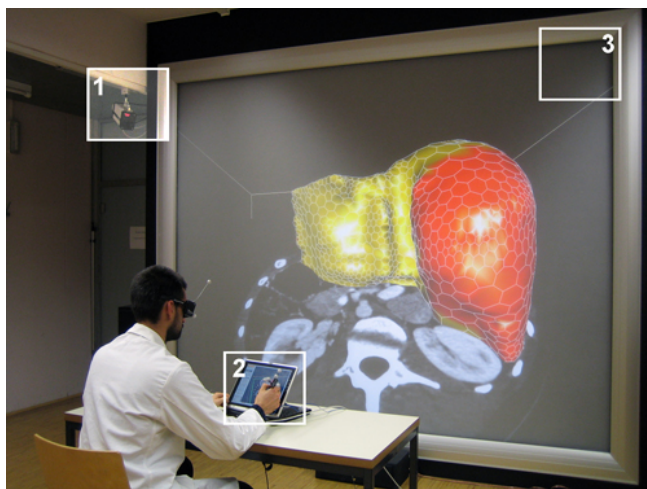
3 HYBRID USER INTERFACE

Figure 1: Hybrid Setup: camera of the optical tracking system (1), Tablet PC and *Eye of Ra* (2), stereoscopic large screen projection system (3).
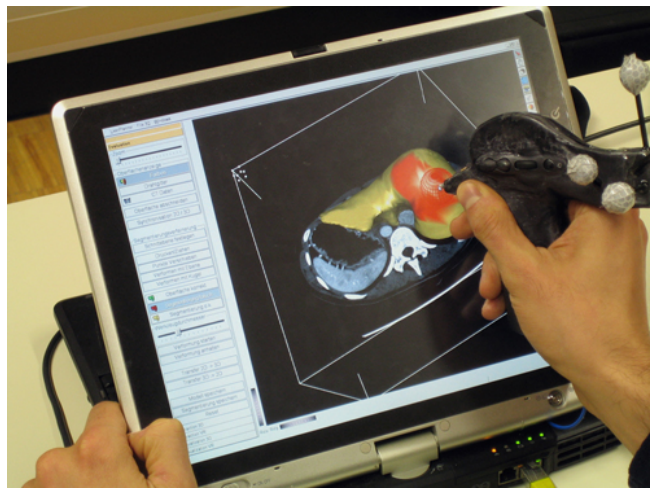

Figure 2: Desktop Setup: Tablet PC with conventional 2D User interface for system control; 2D view for viewing and interaction with the dataset using the *Eye of Ra* input device, which behaves similar to a conventional stylus in the desktop setup.

3.1 Hardware Setup

The hardware setup consists of two main parts, the VR system and the 2D system. The VR system's display is a large stereo wall (stereoscopic back projection screen, 375cm diameter, 1280x1024 pixels) viewed with shutter glasses. A Barco Galaxy 3-chip DLP projector provides high quality active stereo rendering with very good channel separation, which is important when displaying virtual objects close to the user. The stereo wall is driven by a PC workstation (dual 3GHz Xeon, NVidia Quadro FX 3400). Optical tracking of the user's head and the input device is done using an 4-camera infrared system from Advanced Realtime Tracking.

The desktop system is a Tablet PC (Toshiba Portégé M200, 1.8 GHz CPU, GeForce Go 5200 graphics card, 12-inch TFT touchscreen at 1400x1050 pixels). The Tablet PC is placed on a desk approximately 2 meters in front of the screen, tilted at approximately 60 degree for convenient readability. The user is seated at the desk so that both stereo wall and Tablet PC are within the field of view as shown in Figure 1.

3.2 Hybrid Interaction

When referring to hybrid interaction, it is important to differentiate between two approaches: serial and parallel integration. Using serial integration, 2D and 3D methods are used in a sequential order, one after each other. In parallel integration, 2D methods are quasi embedded and used directly to control and adapt the data in the immersive environment. In the virtual liver planning system, the interaction makes use of serial integration, in which the 2D and and the VR system are two separate systems that can be synchronized.

The combination of 2D and 3D interactions can have considerable advantages. 2D actions can be performed with relatively high precision, whereas 3D actions are executed at high speeds in specific task situations. As such, a clear speed-accuracy trade-off can be noticed, depending on the task at hand. In that respect, the virtual liver planning application contains actions that are inherently 2D (like contour editing or point-based segmentation refinement) or 3D (including visual inspection of mixed data, or approximation of surfaces).

The main factor is the flow of action at macro and micro level, for which the mapping and mode changes of functionality, the synchronization of desktop and spatial environments and the focus of

attention play a key role.

At macro level, the performance of the actions is influenced by the work process preferences of the end-users: the radiologist prefers the desktop, whereas the surgeon can better work within a spatial setting. In order to access the functionality, an effective system control method is needed, that allows consistent interaction at both desktop and spatial environment. Redundant mapping of functionality is deliberately chosen, in order to support the work preferences of the end-users: all actions can be performed in the desktop and the spatial environment.

At micro-level, one of the issues that affect the flow of action in an application is the effectiveness of performing mode changes. The high amount of functions cannot be accessed effectively by any of the currently available 3D system control techniques. Therefore, the only possible way for mode changes is to access most of the functions on a standard GUI-style menu on the desktop screen. However, to support frequent interaction loops in the immersive environment, some functions are mapped to the input device. Specifically, manipulation actions are mixed with visual inspection actions (e.g. navigation) at high regularity. Therefore both CT data movement and general camera movement actions are directly mapped to two buttons on the input device.

Due to the different locations of the desktop display and the stereo wall in relation to the user, switching between desktop and spatial interaction (for example during mode change) necessarily results in a change of visual focus. Best practice demands that head rotation and focal plane difference are as limited as possible, without the desktop display occluding the stereo wall.

In the current hardware setup, the Tablet PC is placed at a table, and put in a tilted angle towards the users. The user can conveniently use the touch screen for selecting menu items or manipulating objects. The user's arm may be placed on the table to reduce fatigue. The table is placed at a specific distance from the stereo wall, so that stereo objects are viewed in a depth place that seems to be above or just behind the visuals viewed at the desktop screen. Consequently, both the angular movements of the head are limited, as well as the change of focus between depth planes. There are still field of view differences. Combining a smaller stereo wall with a larger touch screen in an L-shape like configuration may improve this issue.

Performing the different actions in desktop or spatial mode necessarily leads to different kinds of input. In the spatial environment, most actions are coarse, mixed with some more fine-grained actions, whereas at the desktop, all actions are fine-grained. The different kinds of performances, and the necessity to make use of a pen-like device to control the touch screen lead to different kinds of dynamical coupling between hand and device. This is mostly caused by the different kinds of grips to the device that match the precision needed to perform the task, as will be illuminated in the next section.

3.3 Hybrid Input Device

For the design of the new device, a close analysis of the tasks and the associated hand-device couplings and movements was made. In initial tests, a specific device for two-handed interaction was not found necessary because all tasks could be performed well with one hand. However, we observed that the device would need to allow for both power and precision grasps. Rotational movements for putting clipping plane or CT data plane are generally performed in high-speed and lower accuracy (sweeping task), whereas other tools like deformation demand lower speed and higher accuracy, and are better performed in precision grip.

To get an idea of a basic form of the device, we tried to match the movement and rotation patterns to existing devices. It was found that the hand activity matches partially a flying mouse, partially a pen-like device. The pen characteristics were considered important, since the device needed to function as pen-input device for the Tablet PC.

This resulted in an attempt to merge flying mouse and pen shapes into one single design, which allows for an unobtrusive switching between power and precision grasps. From clay models, we arrived at the shape shown in Figure 3. Due to the visual shape of the device, it was nicknamed *Eye of Ra*. The form needed to be large enough to enclose the electronics, which were taken from an EZ5 Optical Pen Mouse, which has a very small circuit board. The wireless connection was tested and found suitable when combined with a longer antenna in the device. The final device was made from carbon and fiberglass mats layered with epoxy glue, which results in a lightweight yet sturdy surface. The original button casing from the EZ5 was directly included in the design, in order to make a stable connection between device casing and electronics. Finally, the tip of the electromagnetic pen for the Tablet PC was embedded at the front of the device, and retro-reflective markers required for tracking were rigidly mounted on the body of the device.

Figure 3: Eye of Ra - Input device for the hybrid user interface: The tip contains a conventional Tablet PC stylus tip for 2D interaction. Two buttons and a scroll wheel are used to trigger 3D interaction tasks. It is equipped with retro-reflective targets for optical tracking. The device is connected to the Tablet PC via a cable. Note the two different ways of grasping the device, the power grasp on the left and the precision grasp on the right.

The shape of the hybrid interaction device allows for easy switching between flying mouse and pen mode. By pronating the forearm, and slightly changing the position of the fingers (mostly moving the thumb), the user can easily change between the different modes. This allows for dynamic coupling between device and hand without the user actively noticing it.

3.4 Software

Following the overall hybrid approach, the software of the system consists of two collaborating applications, a desktop application and a VR application. Both parts of the system are closely coupled and share a large portion of the code. The dataset is visualized on both systems simultaneously. Interaction with the data can take place in either application, while system control tasks like loading the datasets or setting parameters are limited to the 2D menu system on the Tablet PC. All user interaction is performed using the *Eye of Ra* input device described in Section 3.3, which acts like a normal Tablet PC stylus in the desktop application, while 6-DOF tracking, a scroll wheel and buttons on the device are used to trigger input in the VR application.

Both applications involve 3D rendering based on Coin[1], a scene graph library compatible to the Open Inventor standard. The desk-

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[1] http://www.coin3d.org

top application uses the Qt [2] framework for graphical user interface programming. The VR application is based on the *Studierstube* [24] VR/AR library, which builds on top of Coin and provides handling of VR devices such as stereo wall and tracking as well as convenient programming of 3D interaction with the scene graph.
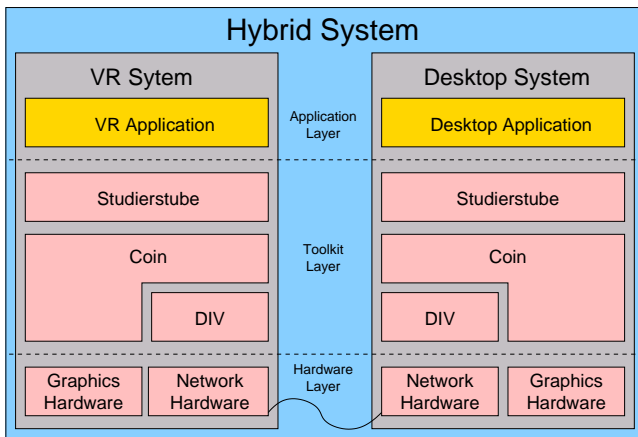

Figure 4: Software Architecture: The two separate applications share data via a network connection based on a distributed scene graph.

Synchronization between the desktop and VR application is based on a distributed shared scene graph extension called DIV [17]. The two applications share synchronized copies of the scene graph, which stores all geometric and application relevant data. Modifications to one copy of the scene graph will be propagated to the other copy, and vice versa. The synchronization happens automatically within the scene graph library, and need not be managed by the application programmer explicitly. Figure 4 gives an overview of the system architecture of the hybrid system.

4 INTERACTION TOOLS

There are three main tasks necessary to improve a segmented surface model:

- **Model Inspection** - The user tries to locate errors in the surface model by comparing raw CT data to the boundary of the surface.

- **Error Marking** - Regions of the surface model that were found erroneous in the inspection step are marked for further processing. This allows to restrict the following correction step to the erroneous regions, and avoids accidentally modifying correct regions.

- **Error Correction** - Marked regions are corrected using special correction tools based on mesh deformation.

Usually these tasks are not performed in a strict order. For example, model inspection is repeatedly required throughout the correction task. Individual corrected parts should be marked as final after successful correction.

The following sections will give an overview of the functionality of the system and the tools provided, mostly from the user's point of view, while technical details of the implementation of the segmentation refinement tools will be described in Section 5.2.

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[2]http://www.trolltech.no/products/qt

4.1 Model Inspection

The first step, model inspection, can be performed on the Tablet PC screen using the *Eye of Ra's* tip for interaction with the rotation, movement and scaling controls in the 2D user interface. In VR the model can be moved and rotated by pressing the scroll-wheel button on the input device, which fixes the model to the input device, while moving the device. The model navigation feature is bound to the scroll-wheel and is permanently available.

CT data is visualized on a 2D cutting plane that can be arbitrarily placed inside the CT scan volume. On the Tablet PC the plane can be manipulated by dragging 3D control widgets provided by the scene graph library. In the VR system the cutting plane, visualized as a rectangle attached to the input device, can be set by dragging in 3D with a specific button pressed. Like the model transformation, the cutting plane manipulation feature is permanently available.

The user may also configure most visualization parameters. For example, they can choose to show the surface model in any combination of wireframe, Gouraud shading and textured with the CT data. An optional plane clipping the 3D model slightly above the cutting plane allows to inspect the surface model near the clipping plane more efficiently.

4.2 Error Marking

For efficient organization of the correction procedure, the user may mark regions according to the type of observed error by painting a "traffic light" color code - green, yellow or red. Green indicates that a portion of the surface is correct and will be immutable by subsequent correction operations. Yellow indicates that the surface is mostly correct but may be moderately altered from its current state as needed for example to smooth out differences at region boundaries. Finally, red indicates the surface is incorrect and may be drastically altered by the error correction tools. The marking is done by painting on the surface either on the Tablet PC or in the VR environment with a brush of adjustable size.

4.3 Error Correction

The presented system allows for correction of segmentation errors using a number of different tools for interactively deforming the surface representation of the object.

The *sphere deformation tool* consists of a sphere of user-defined radius which can be interactively placed in the datasets. In the VR system this is moved in place by moving the input device, while the tool position in the desktop setup is calculated as the position on the cutting plane corresponding to the 2D position of the cursor. Triggering sphere deformation causes object surface parts located within the sphere shape to be successively moved out of the sphere on the shortest possible path. Therefore, placing the sphere tool so that most parts of it are outside the object, causes its surface to move inwards, while outward movement is achieved by placing the sphere mostly inside the object. Moving the input device, while the deformation tool is active, causes the tool to respond, just like if one was deforming a piece of clay using a real world modeling tool.

The *plane deformation tool* is much like the sphere deformation tools, except that its behavior is similar to modeling using a scraper. It can be used to flatten the object's surface. In the VR system the position and orientation of the tools is directly determined by the input device, while cutting plane and the pen stroke direction define the tool's behavior in the desktop setup.

Fine grained deformation can be achieved using the *point dragging tool*, which can be used to pick individual surface vertices and move them directly to the desired location, while the surface deforms like a rubber sheet in the vicinity. Figure 5 shows a screenshot of the tools described above.

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