Anatomic Hepatectomy Planning through Mobile Display Visualization and Interaction

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Abstract. Hepatectomies are resections in which segments of the liver are extracted. While medical images are fundamental in the surgery planning procedure, the process of analysis of such images slice-by-slice is still tedious and inefficient. In this work we propose a strategy to efficiently and semi-automatically segment and classify patient-specific liver models in 3D through a mobile display device. The method is based on volume visualization of standard CT datasets and allows accurate estimation of functional remaining liver volume. Experiments showing effectiveness of the method are presented, and quantitative and qualitative results are discussed.

Keywords. Augmented Reality, Surgery Planning, Human-computer Interaction

1. Introduction

Anatomic hepatectomies [1] (anatomic liver resections) are used for treatment of liver tumor patients. The term "anatomic" indicates that all afferent and efferent vascular elements are dissected, isolated and sectioned before the main phase of exeresis (extraction) of the compromised lobes. An accurate evaluation of the anatomy and volume of the hepatic lobes is essential in planning hepatectomies. This is due to the presence of considerable variations in the internal vascular structure of the liver and consequently in the distribution and volumes of the hepatic lobes [2,3]. A careful evaluation of the vascular structure should also account for the loss of functional tissue due to areas of stasis and ischemia caused by cutting venous and arterial branches. This contributes to prevent postoperative hepatic insufficiency, especially when the volume to be resected is large [4].

Planning hepatectomies involves, in addition to medical knowledge, a computational procedure which allows boundary determination of the liver on tomographic images. This process is called segmentation, and it is also necessary to calculate liver volume. Although liver segmentation in computed tomography (CT) has already motivated a number of research works, its practical application still represents a major challenge. Besides

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Figure 1. A use case: photograph of a physician using the system with a tablet mobile display.

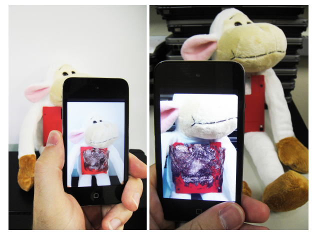


Figure 2. Concept of a medical visualization tool running on the Apple iPod Touch.

organ segmentation, accurate and fast classification of the liver functional segments is crucial in liver tumor extraction as this procedure is significantly influenced by the estimation of the volume of the liver and its anatomical subdivisions. This is a major issue because the estimated percentage of remaining liver tissue may affect the decisions made in surgery planning and even make the procedure inviable [5].

This work proposes a new methodology for liver surgery planning using computer assisted image segmentation and classification of the liver segments. More specifically, we propose an environment for CT segmentation based on a combination of image processing and computer graphics algorithms to quickly extract the liver shape and volume from a general dataset. At the same time, we propose a classification tool to interactively extract the vessel branching within the liver and define the areas affected by both the portal and venous systems. Such tool is based on augmented reality (AR) for interactive visualization of the volume generated from CT. The system allows for the analysis of inner body structures by pointing the mobile display directly upon the body.

2. Materials and Methods

2.1. Development of an Interactive Spatially Aware Visualization System

Using a mobile device (tablet PC) as a see-through display, the system allows the visualization of internal structures of the body. With the help of a webcam, the display shows a real time image of the real world behind it as if it were a window to the world. At the same time, the system generates a visualization of the CT image volume which is mixed to the real world image on the display, augmenting the reality. After a tag is conveniently placed on the patient's body, AR permits the association, in a common space, of medical image volumes to the real body from which they were taken. In practice, the user acquires "X-ray vision", through the tablet PC display to look directly into the patient's body, as in Fig.1.

The volume viewer has been implemented based on the paper by Engel, Kraus and Ertl [6]. The choice was based on: high framerates on common hardware; good quality with few slices and pre-integration table; possibility to change the parameters for the transfer functions. The implementation uses C++ language, OpenGL and CG shader language. The volume viewer allows changing the camera angle and position, and changing the center and width of the density visualization range – also called window – for viewing different materials (tissue densities) in the body volume. We used touch and slide on the screen to control the density window parameters.

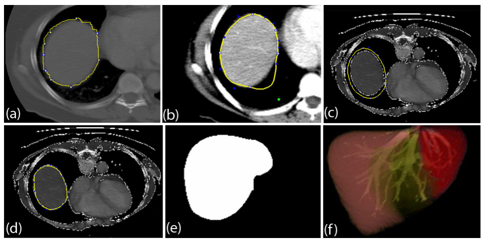


Figure 3. Liver segmentation.

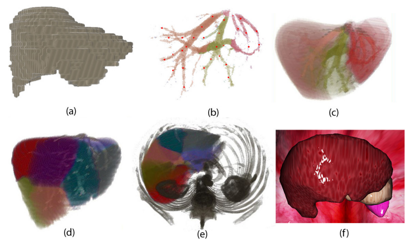


Figure 4. Segment classification.

AR interaction techniques are used to control the OpenGL virtual camera, allowing the volume to be visualized according to the position and orientation of the user handling the mobile display. In AR systems with mobile devices, it is necessary to capture the real world with a camera for display and tracking. We used the ARToolkit library to track tags on the video captured in real time.

2.2. Liver Segmentation with SmartContour

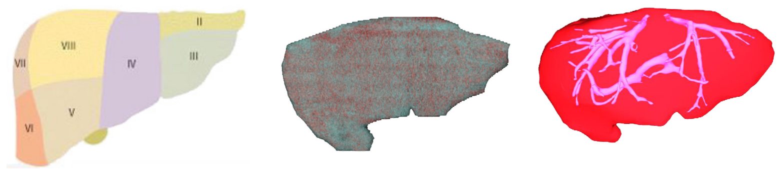
We developed the SmartContour program as a tool for semi-automatic segmentation of a CT dataset. The input is a stack of ordinary CT images. The program first processes the images to increase contrast. An implementation of the live-wires algorithm [7] is then used in every slice of the dataset. In practice, a user is required to click somewhere on the liver border to define a start for the contour. After, by moving the cursor, the program automatically proposes a contour line from the starting point to the current cursor position. New clicks have to be applied only when the proposed contour does not follow the organ edge. With standard CT images, about 10 clicks are required to define a fit contour for one slice (Fig.3a). Using a stylus-based touch screen, as with our system, eases the clicking task in relation to using a mouse.

After this contour is entered, it is sampled for control points and a Bézier spline is created which is a smooth vector information that eliminates the dent effects caused by image resolution (Fig.3b). Such curve is copied to the next slice and the live-wires algorithm is applied to its control points to fit the new contour. It is usually necessary to manually adjust a few points between slices. Fig.3c and d show an optimal case where no manual adjust was needed. In a short time, every slice will contain a contour which is used to separate pixels inside the liver (white) from pixels outside (black). This new black-and-white dataset (Fig.3e) can be used as a mask to define a segmented liver (Fig.3f) and to measure the total volume of the organ.

2.3. Vessel Classification with LiverSegments

We developed the LiverSegments as a tool to classify regions of a volumetric model of the liver according to the 8 anatomic regions defined by Couinaud and known as Couinaud segmentation [1]. Such classification is made interactively by selecting vessels directly in three-dimensions on the segmented volume data described in the previous subsection.

The input to the program is the segmented data from SmartContour and the original CT. The system applies transparency between the parenchyma and the vessels, making them visually more solid and uniform as in Fig.4 b and c. Having a 3D view of the ves-



(a) Couinaud (b) Volume: $1168.46cm^3$ (c) Volume: $1141.78cm^3$

Figure 5. Model of the liver functional segments distribution according to Couinaud [1] (a). Segmented liver with volume information obtained from a CT workstation (b) and with our method (c).

sels, the user is required to insert points on the vessel tree to label the veins as belonging to each of the 8 segments of Couinaud. Using the spatially aware AR interface, the user moves the display around the patient to explore the vessels structure, minimizing the nearer-farther ambiguities often caused by projecting on a 2D screen. The user can precisely select the locations on the vessels to insert the classification points. Then the system labels all voxels of the liver according to their distances to those points. We used the same strategy of a Voronoi diagram which describes a spatial decomposition by means of the proximity of the regions with a given set of points.

2.4. Surgery Planning

Diagnostic and planning start with the CT acquisition. Conventional contrast injections are used, and datasets are then exported in DICOM format from the CT scanner. They can be imported into the SmarContour for segmentation.

After liver segmentation, SmartContour exports both the original images and a 3D segmentation mask. This information is the input to LiverSegments, where the user inspects the 3D volume of the liver, showing or not the surrounding organs (Fig.4e). At this point, the total volume of the liver is also calculated and displayed. Then, interactively, the user sets the center and threshold of the density window for visualization. Selected density ranges are set to transparent allowing the vessels to be highlighted (Fig.4b). The user is then able to classify the liver segments (for example, Couinaud's) by clicking on vessel branches directly on the 3D view. Such branch selection eventually produces a color distribution not only on the vessels but also on the neighboring regions of the parenchyma (Fig.4 c and d). Each colored region corresponds to one functional segment. Borders between these regions are suggested as incision lines for surgery.

3. Results

We performed comparative experiments to evaluate the SmartContour and the LiverSegments in the context of volume estimation for hepatectomy planning. The tests are based on 4 CT datasets and have been performed on a Core 2 desktop PC. Our hypothesis is that liver segmentation and volume estimation from CT using our methods are at least as accurate as the ones obtained with the workstation attached to the CT scanner.

Fig. 5 b and c compare a typical CT workstation segmentation with our methods segmentation for the same dataset. Notice that the very organic shape of our result is closer to the actual anatomy. Table 1, in turn, compares the volume data obtained during

id	Gender	Age	Slices	V. Works.	V. Smart	Diff.
1	M	27	354	1337.84	1353.50	1.16%
2	M	54	377	1814.74	1753.46	3.49%
3	M	43	345	1508.39	1491.72	1.12%
4	F	71	169	1168.46	1144.98	2.05%

Table 1. Comparing volumes: CT workstation vs. our method.

the tests by the CT scanner workstation (V.Works.) and our method (V. Smart). For decision making, the CT workstation calculated volume is trusted to have an error margin of 10%. Notice that the volume calculated with our methods is close to the CT workstation by a monotonous margin inferior to 5%.

Our system has been conceived to cope with the current increase of mobile and pervasive computation. Current mobile devices incorporate convenient orientation sensors, like gyroscope, accelerometer and magnetometer. We obtained preliminary results using the Apple iPod Touch as presented in Fig. 2b.

4. Conclusions and Discussions

The interactive data visualization for preoperative planning provided by our tools allows for thoroughly analysis of the liver directly in 3D and in its actual location along with the patient's body, which is far more comprehensive than usual methods. The system allows for a novel paradigm of interactive study of the human anatomy. In addition to surgery planning, a system like this could be used to teach anatomy and pathology, and in the doctor's office, helping them to communicate with patients and relatives.

Our algorithms run in commodity PC, and the system has been built up with low cost software components, which tremendously increases direct access to surgeons.

Acknowledgements

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