Augmented Reality based Measurement Tools for Liver Surgery Planning

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Abstract. Quantitative analysis is of major importance for various medical applications, especially for liver surgery planning, where physicians rely on exact volume and distance information for elaborating resection proposals. This paper presents a new approach comprising intuitive measurements by using Augmented Reality facilities. Besides two fast volume calculation algorithms, different Augmented Reality based 3D distance measurement methods are presented and usability aspects for such a system are identified.

1 Introduction

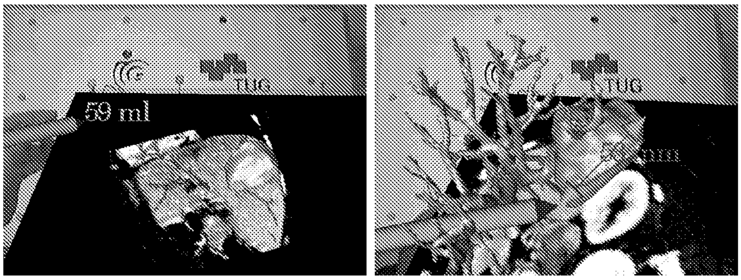
Quantitative measurements are of major importance in various medical disciplines, i.e. for planning tumor resections in liver surgery, where precise measurements of distances and volumes are required. Various 3D-oriented measurement toolkits are available for desktop-based systems, however by using 2D input and display devices, they do not provide an intuitive user interaction. Especially distance measurements between complex vessel structures and tumors demand easy 3D user interaction.

Augmented Reality (AR) based methods presented in this paper cope with these problems by providing alternative 3D input and output devices. As *Augmented Reality* is often misunderstood in literature we use Azuma's well-known definition of this term [1]: Augmented Reality combines real and virtual objects, is interactive in real-time, and is registered in 3D which means that space is used as interaction. An AR system is therefore decoupled from traditional user input devices like mouse or keyboard and uses real 3D interaction devices with 6 degrees of freedom (DOF). Using a stereoscopic AR output device like a head-mounted display or a projection wall allows for 3D visual perception and easy interaction with virtual objects.

2 Related Work

In literature, several approaches for 3D volume and distance measurements can be found. However, the vast majority are desktop-based and face problems with

Fig. 1. AR based (left) volume and (right) distance measurements in the LSPS.



user interaction. Preim et al. have presented different 3D interaction techniques for quantitative analysis of spatial relations. In their work, they have introduced 3D widgets like distance lines or rulers as well as a volume estimation for not segmented data [3,4]. In clinical practice, commercial radiological workstations also provide facilities for 2D and 3D measurements, but facing similar interaction problems. Working with complex 3D structures on a 2D display device requires special 3D manipulators and additional depth cues to provide either measurement tools or a sufficient visual perception. Two-handed virtual manipulators are often the only solution for interacting with virtual 3D objects.

Our proposed work differs from these approaches by the fact, that our AR based system facilitates both, 3D visual perception and a real 3D user interaction with 6 DOF devices. The presented methods are parts of the AR based liver surgery planning system (LSPS) [2] and use all advantages of AR to provide an intuitive measurement toolkit. In this system, a tracked panel and pencil act as AR input devices which allow easy 3D user interaction.

3 Methods

In the following section, two different measurement tools facilitating liver surgery planning are presented. The first one describes two methods which are used for volume calculation of segmented data. The second method shows different AR based distance measurement techniques like point-to-point or snap-to-object modi considering different usability aspects. As our system has the constraint of being real-time interactive, fast execution of both methods must be guaranteed.

3.1 Real-Time Volume Calculation

We have implemented two different volume calculation methods and have compared both in terms of run-time and accuracy. The first approach comprises a graphics hardware-based voxelization to get the volume of a given surface, whereas the second method applies geometric operations directly on a triangulated surface. The input for both methods is a surface-based representation of segmented objects. Due to interactive surface modification (e.g. segmentation refinement [2], or cutting) sophisticated algorithms for volume calculation are necessary.

Voxelization. The first method is carried out by a voxelization, which is the process of approximating a continuous surface representation by a discrete voxel space. In our case, this is done on the graphics card by rendering the surface in an off-screen buffer. As prerequisite, the surface must be in binary format, this means that background color is black and surface color is white. After the surface model is loaded into the graphics card the scene is rendered slice-by-slice according to a given voxel size. During rendering all surface points are displayed as white pixels. However, the interior pixels of one surface slice remain black. As we desire a solid voxelization for volume calculation we have to apply the hardware-supported XOR operator to get interior voxels. The voxel v in a certain slice of the volume can therefore be defined as:

$$v(x, y, i) = s_i(x, y) \oplus v(x, y, i-1),$$

where s denotes the pixel value of one slice. If a voxel once gets filled, it stays filled until a consecutive border pixel on the same (x,y) ray is rendered. The volume data is retrieved from the graphics card by read back each slice separately. Further details of this algorithms can be found in [5]. The run-time of this algorithms depends on the number of triangles and the desired voxel size. Moreover, quantization errors occur due to discretization depending on the voxelization resolution.

3D Gauss-Elling Method. The second algorithm is based on geometric operations which are applied directly on the triangular surface without having any voxel information. This volume calculation can be performed on the CPU and the run-time only depends on the number of triangles.

The main idea of this algorithm is to use a 3D version of the *Gauss-Elling* method which originally calculates the area of a given 2D polygon. The polygon is decomposed into triangles always including one reference vertex v_{ref}. The overall area of the polygon is calculated through summing up all sub-areas spanned by $(v_{ref}, v_i, v_{i+1}, \forall v \in \mathbf{R^2})$. For the 3D case, the *spat-product* is used to get the volume of a spanned tetrahedra and is defined as the following:

$$spat_{tet} =< \boldsymbol{a}, \boldsymbol{b}, \boldsymbol{c} >:= \boldsymbol{a}(\boldsymbol{b} \times \boldsymbol{c})$$

where $\boldsymbol{a}, \boldsymbol{b}, \boldsymbol{c}$ are vectors in $\mathbf{R^3}$ which span a tetrahedra with the reference vertex v_{ref} and one triangle (v_i, v_{i+1}, v_{i+2}) (e.g. $\boldsymbol{a} = \overline{v_{ref} v_i}$). By using this *spat-product* the volume of the spanned tetrahedra $(v_{ref}, \boldsymbol{a}, \boldsymbol{b}, \boldsymbol{c})$ can be defined by

$$v_{tet} = \frac{1}{6} spat_{tet}$$

The complete version of the 3D *Gauss-Elling* algorithms can be described as:

```
∀ triangles tri_i in the mesh do
    span tetrahedra with reference vertex v_ref and tri_i
    add tetrahedra volume to global mesh volume
done
```

The reference vertex v_{ref} can be selected arbitrarily, however, usually one vertex point of the mesh is selected. In contrast to the voxelization algorithm, no quantization errors occur for this numerical solution.

Volume Calculation in Augmented Reality. After explaining two different volume calculation algorithms, their integration into the LSPS is discussed where user interaction should be kept very simple. The measurement starts by selecting the volume calculation mode. Then, the user has to move the pen into the desired object (e.g. liver). As soon as the pen is inside, immediate visual feedback is given by changing the object's color. The volume is calculated on-the-fly by pressing the button on the pen. The quantity information appears on the top of the pen and is user aligned. This textual information can be positioned anywhere in 3D space in a drag-and-drop manner (see Figure 1 (left)). If one object is inside another one (e.g. tumor is inside the liver), one can hide the surrounding surface and then measure the interior objects.

3.2 Augmented Reality based Distance Measurement

Besides volume calculation, our tool currently comprises two different AR based distance measurement methods: *point-to-point* and *snap-to-object*. The main contribution of our approach is its integration into an AR based system (see Figure 1 (right)). Therefore, we are addressing several usability aspects which are necessary for an intuitive AR based distance measurement toolkit:

- The measure line always has two modifiers (e.g. cones) to signal the beginning and the end.
- The measure line and text are always on top and visible.
- As the virtual scene can be arbitrarily moved, the measure text is always viewer-aligned.
- In order to allow precise measurements, a zoom function is implemented which magnifies the whole scene.
- Measurements are easily adjustable by repositioning their modifiers.
- The font of each measure text is scaled according to the minification or magnification.

These usability ascpects have been identified by an evaluation process and are considered in our system. Moreover, we have also integrated a *snap-to-object* mode which is useful if a minimal distance between two objects is desired. According to the current pencil's position, the next border vertex of the nearest object is searched (using a *kd*-tree). By pressing the button the first modifier snaps to this nearest object's vertex.

4 Results and Discussion

As far as voxelization is concerned, in-depth results can be found in [5]. In order to compare the voxelization and the *3D Gauss-Elling* approach, we have created a gold standard dataset by segmenting a patient's liver manually. A surface representation has been generated and both methods have been applied. The relative error compared to the gold standard are 1.6% for the voxelization method (256x256x96 res.) and 1.7% for the *3D Gauss-Elling* method. In terms of run-time, the second approach is about 45 times faster than the voxelization method.

The AR based measurement tools have already been tested by several physicians. Different tasks (e.g. measure distance between two objects, or estimate relative volumes) have been defined and carried out on a desktop-based system used in clinical routine and our AR based system. This evaluation is currently ongoing, and final results will be published soon. Especially for volume estimations of 3D objects, physicians stated advantages of an AR based system because of better visual perception. This is also conform with preliminary evaluation results where estimations in AR are more accurate than in 2D or 3D (desktop-based).

Concerning distance measurements, preliminary results have shown that measured distances are often longer in the AR and shorter in the 2D case compared to the real distances. Moreover, we have observed that the learning curve of an AR system is steeper than with a desktop-based system because user interaction is more intuitive.

5 Conclusions

The presented AR based volume and distance measurement toolkit provides necessary quantitative information for surgeons during elaborating a resection plan in liver surgery. We are currently under way to setup the LSPS at the University Hospital Graz in order to enable physicians to test our system with real-life patient's data. Their feedback and suggestions are of major importance and are regarded for further developments.

Acknowledgement

This work was supported by the Austrian Science Foundation (FWF) under grant P14897.

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