

Integration of Measurement Tools in Medical 3d Visualizations

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Abstract

We discuss 3d interaction techniques for the quantitative analysis of spatial relations in medical visualizations. We describe the design and implementation of measurement tools to measure distances, angles and volumes in 3d visualizations. The visualization of measurement tools as recognizable 3d objects and a 3d interaction, which is both intuitive and precise, determines the usability of such facilities. Measurements may be carried out in 2d visualizations of the original radiological data and in 3d visualizations. The result of a measurement carried out in one view is also displayed in the other view appropriately. We discuss the validation of the obtained measures. Finally, we describe how some important measurement tasks may be solved automatically.

CR Categories and Subject Descriptors: I.3.6 [Computer Graphics]: Methodology and Techniques – Interaction Techniques, J.3 [Computer Applications]: Life and Medical Sciences

Additional Keywords: medical visualization, computer-assisted surgery, quantitative analysis, interaction techniques

1 INTRODUCTION

The quantitative analysis of spatial relations in medical visualizations is crucial for many tasks in diagnosis and treatment planning, as for example in the preoperative planning of oncologic surgery. Currently, it is common practice in radiology to use 2d measurement tools for the definition of distances, diameters, areas, or angles in planar slices of radiological data. This, however, gives only a rough estimation for spatial measurements such as the extent of a 3d object. In particular, the volume of 3d objects can only be estimated roughly. Therefore, tools are required that integrate measurements in 3d visualizations. The development of measurement tools to be used in the context of a complex 3d visualization is difficult because the user has to be provided with enough depth cues to assess the position and orientation of such a measurement tool. A “simple” transition of existing line-based 2d measurement tools into 3d is not sufficient. Even the most advanced radiological workstations, such as SIEMENS VIRTUOSO and PHILIPS EASY VISION, provide at best such basic 3d measurement tools.

An important aspect of medical 3d visualization is that 3d visualizations are derived by the analysis of slices of radiological data. Therefore it is desirable to combine 3d views with 2d views of the original slices. For measurement tasks this implies that measurement points should be visible and modifiable within the slice data. While 3d views have the advantage of showing the overall relations, in 2d views each and every voxel of the original CT (Computed Tomography) or MR (Magnetic Resonance) data may be selected precisely.

The interactive use of measurement tools is the most flexible approach, however, it requires a certain effort on the user’s part and might be inaccurate. Therefore, we carefully analyzed which interaction tasks are of primary importance in order to reduce the interaction effort. Most of the measurement facilities described in this paper are primarily used for liver surgery planning [7].

2 RELATED WORK

General facilities for the quantitative analysis of spatial relations in medical 3d visualizations are described by HASTREITER in [5]. Based on a manipulator of the graphics library OPENINVENTOR [14], an interaction facility was developed which provides a measure corresponding to the current extent of that manipulator (in x -, y - and z -direction). With this measurement facility, the extent of a structure of interest can be approximated. Another interaction facility was designed to approximately determine the volume of roughly ellipsoidal shapes, such as for example tumors. For this purpose, an ellipsoid is transformed by the user. As feedback, the volume of the ellipsoid as an approximation to the structure of interest inside is displayed. Over and above these general tools there are specialized applications, in particular in orthopaedic and facial surgery, where certain measurements, such as angles between particular bones or teeth are determined and visualized.

Much work has been spent on reliable volume determination of the brain and of the brain ventricles [3] which are based on a priori knowledge about brain anatomy. Another area of active research is the quantitative analysis of vasculature with the goal to assess vessel diameters and detect stenosis [11].

For a discussion of the 3d interaction with measurement tools the term *3d widget* is crucial. The term *widget* (composed of *window* and *gadget*) is well-established over a long time to characterize an interaction facility with geometry and behavior. The term 3d widget has been introduced by CONNOR [1]. It is now widely used to describe interaction facilities comprising a 3d geometry and a behavior to manipulate 3d objects. Only 3d widgets allow users to directly manipulate objects in a 3d visualization. With direct manipulation, as introduced by SHNEIDERMAN [9], objects are selected via picking and operations are invoked for example by dragging the selected object. This interaction style is intuitive in particular for the manipulation of geometric objects. HAND [4] gives an overview about important concepts in the development of 3d widgets. An important aspect is that 3d widgets are clearly recognizable 3d objects, such that their position and orientation in a 3d model can be evaluated by the user. Depth-cues, like perspective distortion and shadow projection are thus essential in the use of 3d widgets. The study performed by WANGER *et al.* [13] gives hints on the effects which are achieved by using shadow projections and stereoscopic viewing.

3 USABILITY REQUIREMENTS

The usability of measurement tools depends on a number of presentation parameters. Among them are font parameters (size, color), and line style parameters (line width). The selection of presentation parameters is guided by the following requirements:

- *Distinct assignment of measurement numbers to objects.* It should be clearly recognizable to which object or region a measurement refers.
- *Distinct assignment of measurement numbers to measurement tools.* If several measurements are included in a visualization it is necessary that the affiliation of a number to a measurement tool is visualized unambiguously. The placement of numbers and the choice of presentation parameters such as color are important for this goal.
- *Flexibility.* Due to the large variety of the spatial relations to be analyzed and due to personal preferences it is important that the default values concerning font and line parameters as well as units of measurement tools are adjustable.
- *Precision.* Direct manipulation exhibits a lack of precision which is an essential drawback for measurement tasks. Therefore, additional facilities are required to overcome limited precision. Incremental transformations by means of arrow keys (two additional keys are used for 6 degrees of freedom (DOF) interaction) are provided to support the fine-grained modifications. Furthermore, transformations of measurement tools may be specified by numbers. The header information of medical data is employed to define its resolution (size of a voxel) and to guide the precision of measurement numbers.

4 INTERACTIVE 3D MEASUREMENTS

For direct-manipulative measurements all vertices of measurement tools may be translated by means of a six degrees of freedom (DOF) manipulator. We composed such a 3d widget by combining individual point draggers of the OPENINVENTOR library and refer to this 3d widget as *3d translate manipulator*. The geometry of this widget is composed of three orthogonal 3d arrows. The vertices itself are large enough to be easily selected. Spheres and cones are employed to make these vertices selectable independent of the viewing direction.

All measurement numbers are presented using two-dimensional text (*SoText2*) which is displayed parallel to the viewport. Thus numbers remain legible after rotations. As measurements are integrated in a visualization, the font size used for the numbers must be adapted when the camera is zoomed. Otherwise, excessively large or very small numbers might result. To prevent that too many changes occur, the font size is adapted in discrete steps. A sans serif font is used for optimal legibility.

Another aspect of the usability of all measurement tools in 3d is the restriction of the visible data to support selection tasks. For this purpose, six clipping planes are provided which can be interactively rotated and translated. The use of clipping planes is more flexible than a restriction to a region of interest (ROI). The measurement tools are employed in combination with perspective projection as this is an essential depth-cue.

Two 3d widgets, *distance lines* and *rulers*, have been developed to estimate distances in medical visualizations (Sect 4.1 and 4.2). A 3d angular measurement tool is introduced in Sect. 4.3. Finally, a *volume estimator* widget is presented to approximate volumes of anatomic or pathologic structures.

4.1 Distance Lines

Purpose. Distance lines are employed to define distances between objects or diameters. Such measures are crucial for surgery planning e.g. to evaluate whether there is enough space to remove a structure safely or whether a vessel reconstruction is required (if the diameter of an involved vessel is above a threshold).

Geometry. A *distance line* widget consists of two small cones (3d representation of arrowheads) and a thin cylinder (3d representation of the line). As additional orientation aid, distance lines may cast a shadow. To ensure legibility of the number against backgrounds with varying colors, we embed the number in a rectangle. The rectangle is rendered semitransparently to occlude the medical data not too heavily (Fig. 1).

Behavior. The distance line is created with rubberbanding – an interaction style for the creation of graphics primitive where the shape is updated continuously until the mouse is released (see FOLEY *et al.* [2]). The distance number is also updated instantly. The placement of the number is adapted to the line length: if the line is long enough the cylinder is interrupted in the center for the placement of the number. Otherwise, the number is placed near one of the endpoints of the distance line. The distance line is calibrated by exploiting the voxel size attribute in the header information of radiological data.

The vertices can be translated by means of the 3d translate manipulator described above. To ease the translation, snapping may be enabled. With this feature, the endpoint translated by the user is attracted by the surface of an object as soon as the distance is below a threshold. Snapping is provided to support measurements of distances between object surfaces. This feature, however, can only be applied when segmented objects are available.

For the validation of the measured distance it is crucial to identify the measurement points in the 2d visualization as well. Small quadrilateral marks are employed for this purpose. However, as often some 100 slices are involved it is tedious to look for the slice n where a measurement point is located. Therefore the mark is also displayed in neighboring slices. In slice n the measurement point is marked by an opaque quadrilateral and has a close line border. In the vicinity (slices between $n-3$ and $n+3$) the position which corresponds to the measurement point is marked with a semitransparent quadrilateral and a dotted border line (see Fig. 2).

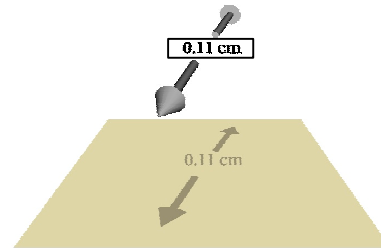


Fig. 1: Distance line and its shadow projection. Here, enough space is available to accommodate the number inside the distance line. The accuracy is adapted to the voxel size.

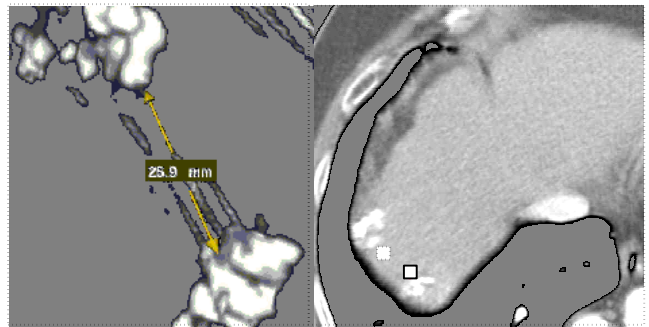


Fig. 2: The distance between two liver tumors is determined with a 3d distance line (left). The two endpoints are also visible in the 2d view (right). The endpoints in the 2d view have been enlarged for better recognizability.

4.2 Interactive Rulers

Purpose. Rulers are well-known measurement facilities from daily life. Within a 3d visualization they are less suitable for a precise determination of distances (for this purpose, distance lines are better suited). However, rulers are useful to roughly approximate the magnitude of structures in a similar way like a scale is used in maps. Also several distances may be estimated simultaneously with one ruler.

Geometry. A ruler consists of a thin cylinder and ticks which represent the scaling of a ruler as well as labels which are attached to some of these ticks. Scales with 0 in the center (by contrast to those with 0 on the left) are preferable for the estimation of diameters. An important design consideration for rulers refers to the recognizability of the ticks. When rulers are freely rotated to adapt to a structure of interest it might happen that the ticks are perpendicular to the viewing direction and thus are invisible. To prevent this, two solutions have been investigated: the first is to use crosses (two perpendicular lines) instead of just one, the second approach is to use circles and thus a two-dimensional mark. The first approach has the advantage that the visualization is less cluttered.

Behavior. A crucial design consideration is the behavior of a ruler when it is scaled. In principle, there are two strategies applicable:

- *Constant distance of labels and ticks.* When a constant distance is kept, the number of ticks and labels is enlarged or reduced proportional to the length of the ruler. This is probably a behavior which meets the user's expectation. However, it may lead to a visualization cluttered by a ruler with many ticks.
- *Adaptable distance of labels and ticks.* The distance between ticks and labels might be adapted to the length of the ruler, for example in such a way that the overall number remains constant. While this approach may prevent that too many ticks and labels appear when the ruler is enlarged, it may be irritating if the distance between ticks changes frequently while the ruler is scaled.

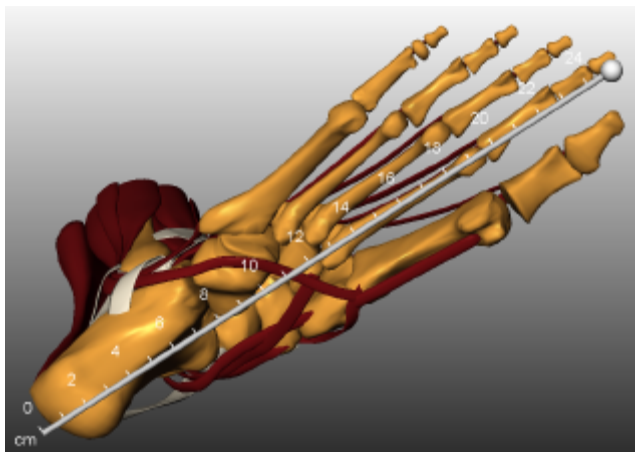


Fig. 3: The ruler is placed inside a surface visualization of the human foot (dataset by Viewpoint Datalabs). Several distances can be approximated simultaneously.

A combination of both strategies seems to be the superior solution: as long as the user is either scaling the ruler or translating one of its vertices (which also affects its length) the distance between the ticks remains constant. If the user does no longer control the ruler, the distance is adapted. The adaptation of ticks and num-

bers, however, is not continuous but instead at discrete levels. The application of the ruler is shown in Fig. 3. When the sphere at an endpoint of the ruler is selected a point dragger appears with six handles to translate the ruler. To remove this dragger, the sphere of the ruler is selected again. In a similar way, a virtual sphere is invoked by selecting the core part of the ruler to rotate it.

4.3 Angular Measurements

Purpose. Angular measurements are carried out to define angles between anatomical or pathological structures. The angle at branchings of vascular structures might be essential for vascular analysis, angles which describe orientations of bones are often important for the diagnosis and treatment planning in orthopaedics.

Geometry. For angular measurements three coordinates are required representing the apex of the angle and terminating the legs. To provide consistency across the measurement tools, we reuse the distance line for this purpose. The angular measurement tool thus consists of two distance lines (which are based on cones and cylinders, recall Sect. 4.1). The apex of the leg is emphasized with a sphere which can be easily selected. It turned out that without orientation aids it is often difficult to assess the size of an angle. Therefore, semitransparent polygons are used as orientation aids when the angle is transformed. The use of semitransparent polygons is an established concept in 3d widget design. It is used for example for some manipulators of the OPENINVENTOR library, such as the Jack manipulator which is utilized to move objects.

Two semitransparent rectangles are created perpendicular to the legs of the angle. Two shapes have been designed to emphasize the plane in which the angle is located. First, the triangle formed by the three vertices of the angular measurement tool is also displayed semitransparently (see Fig. 4). The use of a triangle as orientation aid is restricted to angles of less than 180 degrees (or would be ambiguous for angles larger than 180 degrees). Therefore we have improved the initial design. With the new design, a portion of a circle is employed instead of the triangle to communicate the extent of the angle. The portion is scaled such that the radius corresponds to the half length of the smaller leg. A typical application of the angle measurement tool is shown in Fig. 6. The main advantage of the new design is that no ambiguities occur for angles over 180 degrees.

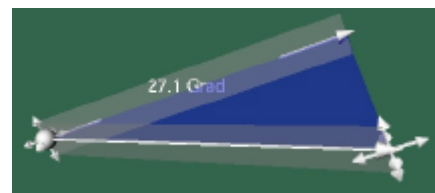


Fig. 4: Initial design of a 3d widget to measure angles with semi-transparent planes as orientation aids. The 3d translate manipulator is used to modify a vertex.

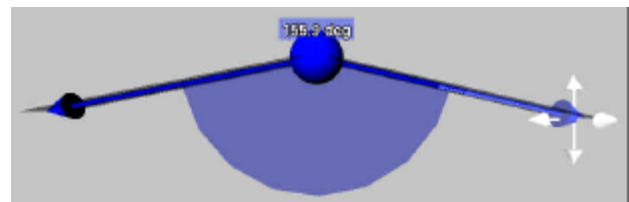


Fig. 5: The improved 3d widgets for the measurement of angles where a semi-transparent segment of a circle is used as orientation aid.

Concerning the placement of the measurement number two strategies have been developed. First, the number has been integrated in one of the two distance lines which represent the legs (recall Fig. 4). The second strategy is closer to the way angles are annotated in conventional technical drawings – the number is placed near the apex of the angle. The second strategy has the advantage that for larger angles the orientation is unambiguous.

Behavior. The orientation aids are only temporarily included to prevent that the visualization is cluttered. Each of the three vertices might be selected and transformed by means of the 3d translate manipulator. While the ruler may be transformed as a whole this facility seems to be of minor importance for angular measurements. In exactly the same way as for distance lines the placement of the number is adapted. If there is enough space to accommodate the number inside a distance line the line is interrupted to place the number. Otherwise the number is placed at the apex (recall Fig. 5). If measurements are carried out for clinical data the three vertices are also displayed in the 2d slice view of the original data. In the 2d view the vertices are marked in the same way as the vertices of a distance line (recall Fig. 2, right). Thus, vertices are visible not only in the slice to which they belong but also in the neighboring slices and they can be translated also in the 2d view.

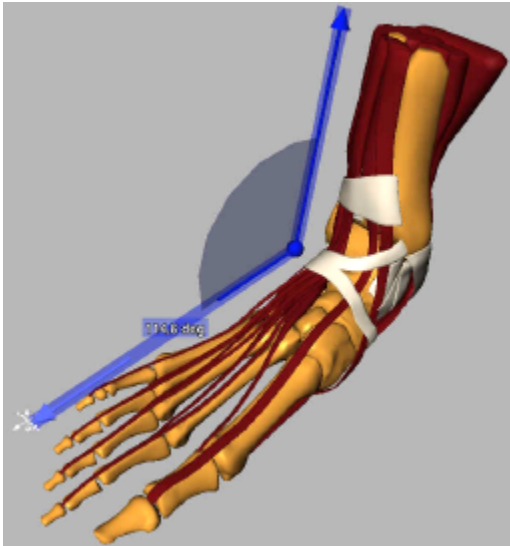


Fig. 6: Measurement of angles in an example inspired by orthopaedic applications. The planes which are displayed during interaction serve as orientation aid. Dataset provided by VIEWPOINT DATALABS.

For angular measurements, a tighter coupling of 2d and 3d views has been developed. When the three vertices of an angle are defined, an MPR view (multiplanar reformatting) is generated. The MPR view is an oblique slice through the volume data which passes exactly spanned by the three vertices of an angle (Fig. 7).

4.4 Interactive Volume Approximation

Volumes of objects can be computed rather precisely if the objects are explicitly segmented. For volumetry it is simply counted how many voxels belong to an object and this number is multiplied by the voxel size.¹ Explicit segmentation of 3d objects, however, is

¹ For small or elongated objects with a large portion of boundary voxels this approach is not reliable due to partial volume effects (the error may be as large as 30%).

tedious, in particular when the objects are not sharply contrasted against their environment and the user has to draw the object's contour manually. Therefore the VOLUMEESTIMATOR, was designed to perform such measurements with less interaction effort.

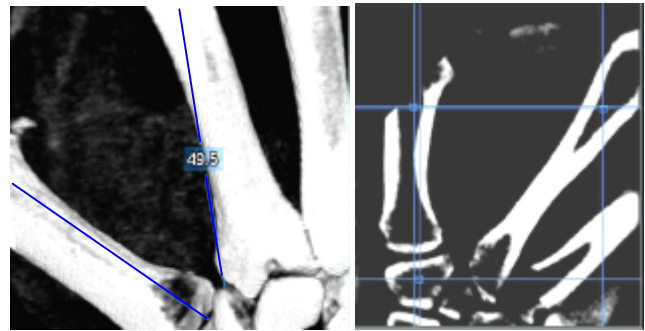


Fig. 7: Measurement of an angle in CT data of the human hand. Left a 3d volume rendering, right a MPR display with the three vertices characterizing the angle.

The basic idea for volume estimation (recall [5]) is that a simple geometric shape is moved inside the 3d volume visualization with the goal to enclose the object for which the volume should be computed. The volume visualization is guided by a transfer function which suppresses structures which are not relevant for the measurement task. The system displays the volume of this simple shape as feedback. This basic idea, however, has two drawbacks:

- It is often difficult to locate an object in a volume visualization. An appropriate specification of the transfer function requires that intensity values of this structure are known and even then it might be difficult to suppress unwanted structures of similar intensity values.
- The volume computation is very sensitive to small changes of the scale. As an example, if the diameter of a sphere is only increased by 10% the volume increases by 33%.

To tackle the first problem, it is crucial that the 3d shape is displayed in the 2d as well as in the 3d view with facilities to modify it in both views. The lack of precision can be diminished by restricting the volume computation to voxels which are inside the bounding object *and* satisfy a condition concerning their intensity values. In particular, it is useful to restrict the volume calculation to voxels with intensity values v in an interval $[i_{low}, \dots, i_{high}]$. As feedback the voxels which satisfy the condition are highlighted in both views so that it becomes obvious whether the "right" voxels are selected. However, the result may depend strongly on the interval chosen. Therefore, the user may specify a second interval: one interval is intended to cover all voxels which belong with highest probability to the structure of interest (the inner interval). The second interval has a larger width in order to cover also voxels where it is uncertain whether or not they belong to the structure. The volume is simultaneously calculated for both, the inner and the outer interval. The difference between the two values indicates the accuracy and reliability of the measurement.

Due to inhomogeneities inside the anatomic or pathologic structures (for example tumors) some inner parts may be outside the specified intervals. This problem gave rise to two changes. First, the user can specify that holes and concave notches of a certain size are closed. This is accomplished with a morphological image processing filter which does not alter the normal surface of a 3d structure. The user can select between three predefined kernel sizes to control the amount of closing (see Fig. 8).

Second, we included a possibility to invert the interval which restricts the volume computation. The invert option means that values within the chosen interval are excluded from the computation rather than included. In some cases, such a specification is better suited to separate foreground from background voxels.

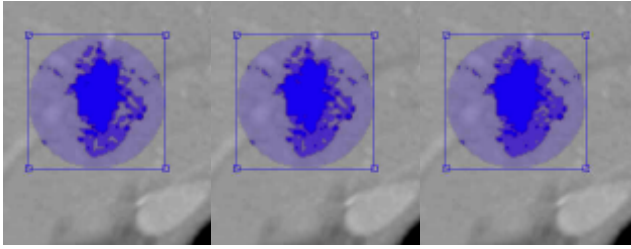


Fig. 8: Effect of a close gap filter on the volume estimation: In the left image no filter is applied. In the middle and right image a filter with size $7 \times 7 \times 3$ and $11 \times 11 \times 3$ is applied, respectively. The volume changed from 3.5 to 3.6 and 3.8 ml for the inner interval and from 7.6 to 7.7 and 8.0 ml for the wider interval by applying the close gap filter.

4.4.1 Efficient 3d Scan Conversion of Volume Shapes

An important issue in the volume approximation is a fast determination of the voxels which are inside the relevant shape. As large medical datasets are involved real-time interaction is not easy to achieve. We restrict the shapes used for volume approximation to convex shapes which can be conveniently defined with implicit functions. These include wedges and cuboids. We employ an algorithm which we have developed for efficient virtual resection [8] and which exploits that objects are convex. We briefly repeat the main idea here: a convex resection region R is defined by an implicit function. With a transformation $T(R)$ it is mapped into a mask volume M , the size of which corresponds to the data volume V . For each voxel $v = \{v_x, v_y, v_z\}$ in V the corresponding voxel $m = \{m_x, m_y, m_z\}$ in M is TRUE if m belongs to $T(R)$. For the fast identification of voxels belonging to $T(R)$, an additional data structure, a brick volume B , is introduced to record which regions in M have been processed. In B one item represents a brick of M with the initial size of $12 \times 12 \times 12$ voxels. Since R is convex it is in many cases sufficient to check the vertices of a brick whether they belong to $T(R)$. If the test yields TRUE for all vertices all voxels of the brick are counted. If the test yields FALSE for all vertices the whole brick is outside $T(R)$. Only if the test yields TRUE for some vertices and FALSE for others the brick is subdivided. The algorithm starts at a voxel inside of $T(R)$, considers its brick and recursively visits neighboring bricks (with subdivision if required) until no neighboring bricks are found which belong to $T(R)$.

The restriction to convex objects does not represent a problem in practical applications where the volume is approximated primarily for lesions or organs. The volume of vascular structures or nerves, for example, which could not be approximated well by convex objects, is rarely relevant.

4.4.2 Usage

Volume estimation with the described measurement tool is typically carried out in two steps. In the first step, a shape is chosen and placed such that it encloses the desired structure completely (ellipsoids, cylinder and cuboids are offered). In the second step, intervals are adjusted to restrict the computation. For the interval specification it is useful to select some points which are inside the structure of interest. As feedback, the intensity value at this posi-

tion is displayed. These values may be used to adjust the interval appropriately. The interval specification may take some time when an entirely new structure is analyzed. However, with CT data, the intensity values for certain structures are similar across different cases which gives rise to standard values which might be stored for later use. For liver tumors in CT data for example an interval center of 40 Hounsfield units and a width of 60 and 80 for the inner and outer interval are often appropriate. The interval specification is not sophisticated; each value is specified with a simple numeric input (a text input and a slider). More advanced would be a threshold selection in the context of the histogram of the defined volume.

Volume estimation within the 3d view requires to specify an appropriate transfer function which makes it possible to see the structure which should be analyzed. In order to evaluate whether the relevant structure is completely inside the 3d shape requires several rotations and transformations of the tool. In this case, not only translations but also scalings and rotations of the measurement tool are required. A JACK-manipulator provided by OPEN INVENTOR is employed for this purpose [14].

Using the 2d view, it is preferable to look first for a slice where the desired structure is rather large and to adjust the scale of the shape with reference to this slice. The use of ellipsoids has the drawback that it is difficult to predict which extent the 2d cross-section has in other slices. Therefore the scaling often has to be modified. Thus, a cylinder is often better suited as an enclosing shape. Whether or not the desired structure is fully enclosed can be evaluated if the border of the structure does not belong to the outer and inner interval (see Fig. 12, next page).

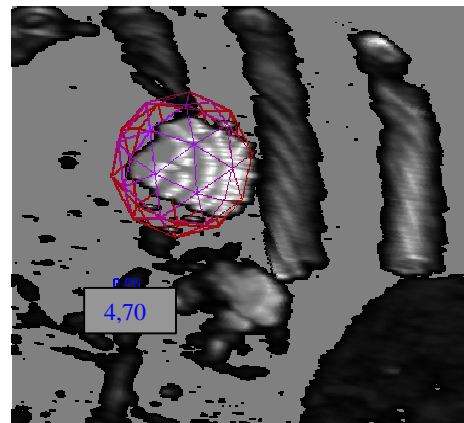


Fig. 9: An ellipsoid (approximated by a polyhedron and visualized as wireframe in the 3d view) is moved inside a 3d visualization. The result is also visible in the 2d view (see Fig. 10).

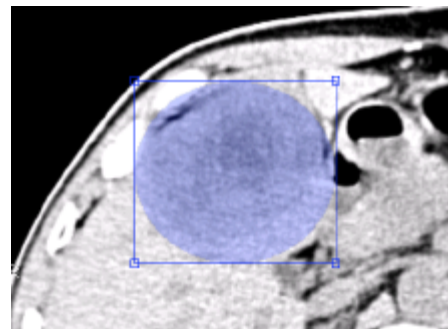


Fig. 10: The 2d representation of the shape is transparently overlaid to the original data in order to verify whether the structure is completely enclosed.

4.4.3 Validation

We have evaluated the use of the VOLUMEESTIMATOR by using it to analyze malignant liver tumors in CT data. This application is relevant because tumor volume is essential for tumor staging as well as for the evaluation of therapies. However, it is very difficult because intensity values have a large variance inside liver tumors. Four liver tumors have been segmented explicitly by manual drawing carried out by a medical specialist in radiology. The resulting volume is regarded as the correct volume (as different radiologists would probably get slightly different results this assumption is a simplification). The liver tumors were independently analyzed with the VOLUMEESTIMATOR. The cylinder shape was chosen in all cases. It was hypothesized that

- (1) that the estimation has the same order of magnitude as the correct result (the mean of the two estimated volumes should be at least 50% and less than 200% of the correct result) and
- (2) that the correct result was between the two volumes calculated with the inner and outer interval.

While the first hypothesis was fulfilled in all 4 cases, the second hypothesis was only in 3 of 4 cases fulfilled. Table 1 summarizes the results. The two numbers for volume estimation refer to the inner and outer interval. Without the image processing step to close gaps the results would be less reliable with systematic underestimation of the volume (for example 42 and 76 ml for case 2 instead of 46 and 87 ml). The influence of the close gap step has recorded in all cases and was found to be 12% on average (minimum: 5%, maximum: 18%). The strong influence of the interval chosen could also be demonstrated: volumes changed up to 30% if the interval center was moderately shifted by 10 Hounsfield units.

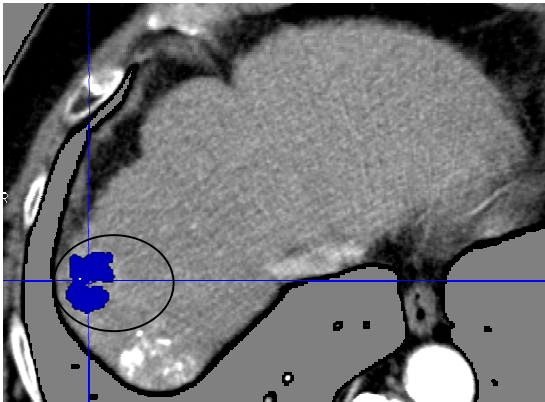


Fig. 11: The computation of the volume for a liver lesion is restricted to voxels with certain intensity values in the underlying CT data (dark blue voxels).

4.4.4 Discussion

Although these results have no statistical significance and are bound to a specific application they give a hint on the usefulness of such measurement tool. The application chosen here is a difficult example because liver tumors are hard to identify with rather weak boundaries. If a specific application, such as tumor volumetry is chosen there are certainly more sophisticated and better segmentation methods available. However, these methods usually require more interaction and/or calculation time. In many situations, absolute volumes are not of primary importance. Often, volumes are important to assess the success of a treatment, such as chemotherapy for a malignant disease. In such cases, it is more important that the method is reproducible and correctly reflects whether or not the volume decreased and how strong it decreased.

Table 1: Comparison of manual volume determination by an expert and volume approximation

Case	Interval (Center; Inner Width; Outer Width)	Volume Estimation	Exact Result
1	40; 50; 75	42; 92	69
2	40; 55; 75	46; 87	82
3	40; 40; 60	130; 231	235
4	40; 60; 80	117; 178	151

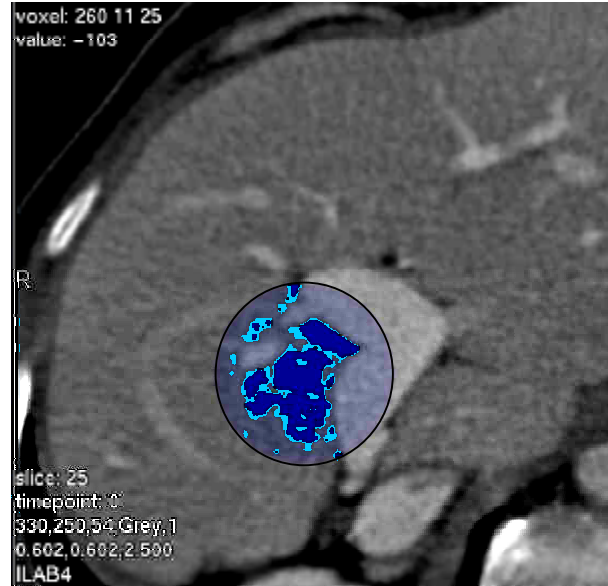


Fig. 12: A volumetry of a liver tumor is performed with the VOLUMEESTIMATOR using two intervals. The regions which are displayed dark blue represent the inner interval (interval width: 50 Hounsfield units). The light blue regions correspond to the wider interval (80 HU). The computed volume is 7.1 ml versus 12.2 ml for the wider interval.

5 AUTOMATIC 3D MEASUREMENTS

Automatic measurements of object properties or relations between objects require explicit segmentation of objects. As a first example for the automatic support of an important measurement task we describe how the extent of objects, for example of pathologic structures, can be defined. The second example is the determination of angles between objects along their longest principal component.

5.1 Definition of Object Extents

The extent of a 3d object o can be characterized by the principal component analysis [10]. In this process, the center of gravity (COG) of o is calculated, the covariance matrix A (a symmetric 3×3 -matrix) is computed taking into account the COG and all vertices of o . The normalized eigenvectors of A form a local right-angled coordinate system with origin at the COG. The normalized eigenvectors of A form a rotation matrix C . In order to get the exact extent in each of the three directions, o is rotated to o' according to C . Since o' is axis-aligned, the axis-aligned bounding

box (AABB) of o' can be easily determined. The length of the axes of the AABB represent the length of the main axis. The extent is visualized by either the longest distance line (Fig. 13) or by three orthogonal distance lines intersecting at the COG (Fig. 14). Numbers are placed at the endpoints to reduce the problem of overlapping numbers. As the distance lines proceed inside, the object for which these measurements have been carried out is rendered semitransparently.

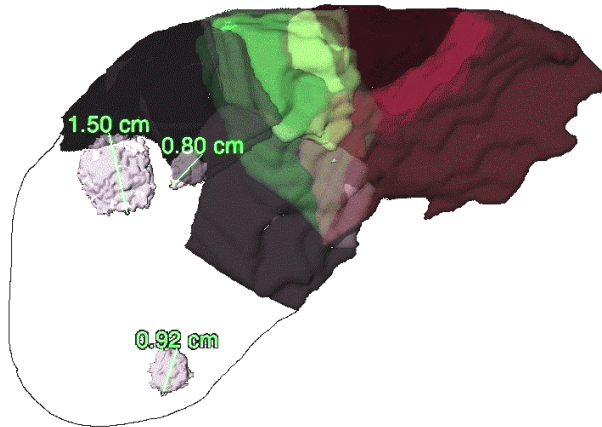


Fig. 13: For three lesions in the liver the longest of the principal components is determined. The liver consists of eight vascular territories called segments. Five segments are displayed with different colors and three segments (those to which the lesions belong) are hidden. The liver outline is manually sketched.

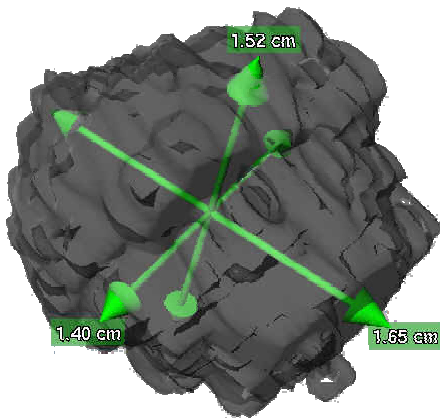


Fig. 14: The extent of a tumor is visualized with three orthogonal distance lines derived from a principal component analysis.

5.2 Definition of Angles Between Objects

A second example of automatic support for a frequent measurement task refers to the angle between two elongated objects. Clinical relevant examples include knee surgery planning. Automatic support can be provided again by utilizing segmentation information and performing a principal component analysis for two objects selected by the user. For automatic angular measurements it is sufficient to know the eigenvector corresponding to the largest eigenvalue for both objects. The angle between these directions is automatically calculated and an angle measurement tool (recall

Sect. 4.3) is placed which communicates this angle. The legs of the angle are parallel to the direction of the computed eigenvectors and the apex of the angle is placed at their cross-section (see Fig. 15). In the rare cases, that the eigenvectors are parallel to each other or warped, this method is not applicable and the user is notified correspondingly.

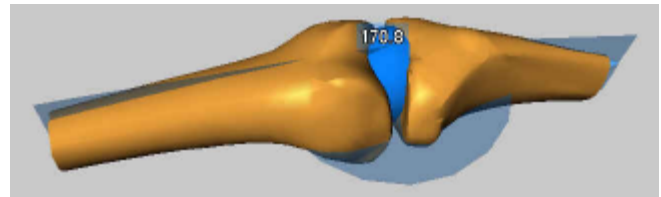


Fig. 15: Automatic measurement of angles between two selected bones based on a principal component analysis.

6 IMPLEMENTATION AND APPLICATION OF MEASUREMENT TOOLS

3d widgets for measurements in 3d visualizations have been developed using graphic primitives from OPENINVENTOR (recall [14]), which provides facilities for 3d interaction: manipulators as complete 3d widgets as well as draggers as elementary components of 3d widgets are available. The development of 3d widgets is carried out by either modifying an existing manipulator or by composing draggers in entirely new ways.

Measurement tools must be named to be selectively displayed, hidden and removed. A suggestion for the name is automatically created (the name is derived from the type and a sequential number of the tool). Also, for the color of measurement tools a suggestion is generated which takes into account that the colors should be discriminated easily and that they can be recognized well on typical backgrounds in gray level visualizations of medical data. Four colors have been selected (a subset of eight colors which are easy to discriminate, proposed in [11]). These colors are used for the first four measurement tools as default values. In the rare case that more measurement tools are used simultaneously, the colors are reused and should be altered by the user. A similar color selection scheme is provided by the SIEMENS VIRTUOSO workstation.

A measurement is stored together with the viewing direction at the time of its specification. Later, the measurement might be selected in a list, and as a consequence, this original viewing direction is reused. Instead of providing the user with an entirely new viewing direction a short animation is generated which allows to observe how the viewing direction changed. This behavior is realized similarly in the PHILIPS EASY VISION workstation.

The measurement facilities are integrated in an application which utilizes two viewers to display the 3d data as well as the 2d slices. The application has a fixed layout with a larger area for the 3d view and a smaller area for the 2d view. The viewers may be exchanged which is useful if the interaction is carried out in the 2d view. The 2d view allows the display of textual information, including the voxel size, the number of slices, the current position within the slice and the slice number. Also the intensity value at the current position may be displayed. This feature is essential for volume estimation (recall Sect. 4.4). Often the user selects several voxels, reads the intensity values displayed and uses this information to specify an appropriate interval. The measurement tools have been realized as nodes of the OPENINVENTOR library by subclassing them from an existing class (SOSEPARATOR). As OPENINVENTOR is available on many operating systems the measurement tools can thus be flexibly reused.

7 CONCLUSION

We have presented generally applicable tools for the determination of distances, angles, and volumes with a focus on applications in medicine. These tools can be used to analyze spatial relations in original data without prior image analysis as well as for the analysis of segmented visualizations. Segmentation information might be exploited to enhance measurements by providing snapping mechanisms and automatic support for well-defined tasks, such as the definition of object extents and angles between objects.

3d measurements support diagnosis and pretherapeutic decisions. The design of 3d measurement tools requires careful consideration of 3d visualization and 3d interaction. 3d measurements in general, benefit from facilities for 3d input or stereoscopic output. OPENINVENTOR with its components for 3d interaction provides an appropriate framework for the development of measurement tools.

The distance line and angular measurement facilities are now integrated in our surgical planning tool, the INTERVENTIONPLANNER (in [8] a preliminary version of this tool is described). This system is used for liver surgery planning in three German university hospitals. In this context, a more in-depth evaluation of the presented measurement facilities is intended. It is important to study how precise interactive measurements are and how well users get along with these new facilities using realistic scenarios from the everyday experience of medical doctors. Informal tests as well as discussions at medical conferences indicate that the automatic measurement of the extent of objects is the most valuable tool for a variety of therapy planning tasks. We also learned from medical doctors that the measurements are useful in order to document preoperative planning and decision making. For the practical use it is desirable to standardize the use of measurement tools by defining adjustable *measurement styles*.

The interaction itself might benefit from two-handed interaction. The simultaneous use of two input devices is useful for many 3d interaction tasks, in particular for applications when geometric objects are involved (see HINCKLEY *et al.* [6]). For measurement tasks, bimanual interaction might be used to control both endpoints of a measurement tool or to control the virtual camera and a measurement tool simultaneously.

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