Interacting with Image Hierarchies for Fast & Accurate Object Segmentation

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1. INTRODUCTION

Object definition is an increasingly important area of medical image research. Accurate and fairly rapid object definition is essential for measuring the size and, perhaps more importantly, the change in size of anatomical objects such as kidneys and tumors. Rapid and fairly accurate object definition is essential for 3D real-time visualization including both surgery planning and Radiation oncology treatment planning.

One approach to object definition involves the use of 3D image hierarchies, such as Eberly's Ridge Flow. However, the image hierarchy segmentation approach requires user interaction in selecting regions and subtrees. Further, visualizing and comprehending the anatomy and the selected portions of the hierarchy can be problematic.

In this paper we will describe the Magic Crayon tool which allows a user to define rapidly and accurately various anatomical objects by interacting with image hierarchies such as those generated with Eberly's Ridge Flow algorithm as well as other 3D image hierarchies. Preliminary results suggest that fairly complex anatomical objects can be segmented in under a minute with sufficient accuracy for 3D surgery planning, 3D radiation oncology treatment planning, and similar applications. Potential modifications to the approach for improved accuracy are summarized.

2. OBJECT DEFINITION TASKS

Rapid and accurate object definition is applicable to a number of applications within medical imaging that have varying requirements as to the accuracy with which an anatomical object must be described and as to the speed with which it must be defined.

Volume Calculation. Extremely accurate 3D object definition is the essential step in volume calculation [1-9]. Volume calculation is the essential step in determining whether anatomical objects, such as kidneys and liver tumors, have changed in size. Size change is essential for many diagnostic determinations. Slice thicknesses will make partial volume effects a problem; partial volume effect occurs when a sizable number of voxels are only half filled with the object in question. The Divergence method [10,11] or a probabilistic approach [e.g., 12] seem to provide an improvement over conventional pixel counting. Required accuracy will vary considerably. With fairly large objects and fairly thin slices, one can do a reasonably acceptable job of volume calculation by hand counting the pixels in each slice of the object. However, this process may take from 10 to 30 minutes per object so it is of no use in the clinic and isn't even used much in research. Relative size determination in the clinic is still calculated occasionally by measuring X and Y dimensions and counting slices, a process that requires only 10 to 30 seconds. Thus, for computerized volume calculation to be clinically useful, we believe we will need extremely accurate 30 second object definition.

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3D Display for Surgery & Radiation-Oncology-Treatment Planning. Object definition has three uses during Surgery and Radiation-Oncology-Treatment Planning [13]. First, anatomical object definitions are used to tile objects for subsequent 3D display using polygonal rendering techniques. Second, object definitions is used to provide a steep contrast gradient during volume rendering. And third, object definition is used to remove objects from volume or polygonally-rendered displays allowing improved visualization of underlying objects; ideally the obscuring objects can be removed and replaced in real time. Fairly coarse definitions are often sufficient for the removal of obstructing objects during 3D visualization and for ensuring that treatment beams do not hit critical anatomical structures.

3. IMAGE HIERARCHY SEGMENTATION

There are many methods of object definition from a single-intensity image; a full survey written by us can be found in [14]. The common methods of object definition can be categorized as follows.

Manual. Many systems allow manual drawing of object boundaries in 2D images. Manual methods are always successful (theoretically), but they can be extraordinarily time-consuming, especially for 3D data sets, where these operations must be done on multiple slices.

Thresholding, Edge Detection, and Region Growing. To utilize these techniques the user selects an intensity threshold, and the resulting region is then automatically contoured with operations such as those from mathematical morphology [15,16]. These methods can rapidly define anatomical objects and operate on several slices at the same time, but they often fail and then require considerable manual editing.

Edge detection and region growing are based on the idea that object *boundaries* are locations where the image intensity (or some other geometric property) changes rapidly. Correspondingly, object *regions* are collections of pixels where the property in question changes slowly. Innumerable edge detection methods have been created based on following a ridge of boundariness, where "boundariness" measures the local rate of change of intensity, maximized over all orientations. Similarly, region-growing methods aggregate pixels until blocked by an adequately-strong ridge of boundariness. The difficulty with these methods is that the high sensitivity of boundariness to noise leads to regular failures in producing the desired object boundary. An attractive variant of these methods — of which a particularly powerful version has been produced in our laboratory — involves variable conductance diffusion of the intensity or other geometric properties [17-19] followed by thresholding. However, even this kind of method can produce only visually sensible regions and not necessarily regions corresponding to anatomic objects in medical images. Further, it still requires careful control in terms of location and scale.

Active Contours. A manually-chosen boundary or one chosen based on a priori knowledge can be warped onto the boundariness ridge by optimizing a cost function that reflects both contour constraints and matches those locations that behave like a ridge in boundariness. This method is quite powerful and has recently been generalized to 3D [20], but it requires significant interaction in choosing the initial contour and in getting over the local minima as the contour warping proceeds.

Multiscale Geometric. Operators measuring geometry at many aperture sizes have been found particularly powerful in determining objects. This method produces image description hierarchies and is based on a series of geometric analyses, most recently based on ridge-flow.

Ridge flow segmentation is a general method for segmenting medical images [21]. The segmented image is represented by a hierarchy which is built using multiscale and differential geometric methods. The leaf nodes of the hierarchy represent small, primitive regions of an image. These regions are constructed by using a ridge flow model, which is a generalization of the peak flow model. In the ridge flow model, a generalization of local maxima, called ridges [22], are identified. The ridges are segmented into curvilinear segments. A ridge segment is assigned a region of points, each point being the initial value for a flow line on the graph of intensity such that the flow terminates at the ridge segment. The flow line directions in this case are determined by the gradient of a function which is in some sense natural to the ridge construction.

The interior nodes of the hierarchy relate the primitive regions in a way that reflects the natural object structure of the image. Each level of nodes in the hierarchy represents primitive regions of an image which have been Gaussian blurred to a selected scale. The larger-scale images are also segmented using a ridge flow model. The idea is that small regions at one scale are blurred into a single larger region at a larger scale. Such small regions will be linked to a parent node at the next level in the hierarchy. As the scale increases without bound, the blurring process yields a constant image. Thus, at a large scale, all nodes will eventually have a single ancestor (the root of the tree). Anatomical objects are obtained as unions and differences of subtrees of the hierarchy.

Dr. Eberly has implemented the ridge-flow algorithms for any dimension $n >= 1$, not just for the usual 2 and 3 dimensions. The image and corresponding hierarchy are used as input to visualization tools which allow the user to interactively define objects by rapidly traversing the hierarchy and displaying the regions of interest with color overlays [23-25].

4. VISUALIZATION TECHNIQUES

Even with perfectly defined sensible regions, a priori knowledge is required to define partially visible anatomic objects. Thus a computer human interaction is required to allow a knowledgeable user to select a set of sub-trees within the hierarchy so that the sub-trees' corresponding primitive regions correctly define the target object. To do this we have developed a 3D object definition tool called the "Magic Crayon" (Figure 2). This tool serves as an interface to object-subobject hierarchies generated by any appropriate algorithm. To work optimally, this tool must 1) allow the user to spatially understand the anatomy in a CT or MR study; 2) allow the user to generate a gestalt of the various levels of the object-subobject hierarchy; and 3) allow the user to rapidly select appropriate regions and subtrees from the hierarchy that together correctly define the target anatomical object.

2D Visualizations. Visualization of the anatomy is critical to rapid and accurate object definition. We have tried three methods: an interlinked tri-orthogonal visualization tool, a mosaic tool and a stacked or cine visualization tool allowing rapid one-at-a-time visualization of the study without inter-image eye movements [26]. These visualization methods each have advantages and disadvantages. Our current version of the Magic Crayon uses a six slice mosaic viewer with 256x256 images as well as a stacked viewer with 512x512 images. We find the stacked display ergonomically near-optimal because the larger images require less fine-motor control for specification of particular anatomy and because anatomy on the next slice can be selected in 0.2 seconds by adjusting the display to the next image, rather than by having to take 0.5 to 1.0 seconds to move the mouse to another image and display the indicated anatomy. The mosaic display is provided to allow the user a visual gestalt of the anatomy surrounding the currently-accessed slice. The triorthogonal viewer is no longer in use because the lack of Z-plane resolution with typical CT studies precluded the third perspective's usefulness relative to the effort required to generate the orthogonal views.

3D Interactive Visualizations for the Magic Crayon. 3D real-time visualization allows the radiologist a better spatial understanding of the anatomical object as it is being defined. But 3D volume rendering has two problems: current volume rendering and other 3D visualization techniques cannot show the soft tissue detail needed to define many objects, and human kinesthetics and available pointing devices limit the precision with which 3D points can be identified. We suspect that a linked combination of a real-time 3D display and 2D presentations would provide superior visualizations not only for anatomical object definition and volume measuring, but also for other clinical 3D visualization tasks such as interventional radiology and surgical planning. Thus we have been exploring adding a linked real-time 3D volume-rendered visualization to our object definition tool. This 3D display will be linked to the 2D views so that objects defined on the 2D views would be reflected interactively on the 3D display, and the user will be able to view the 3D object from any viewpoint.

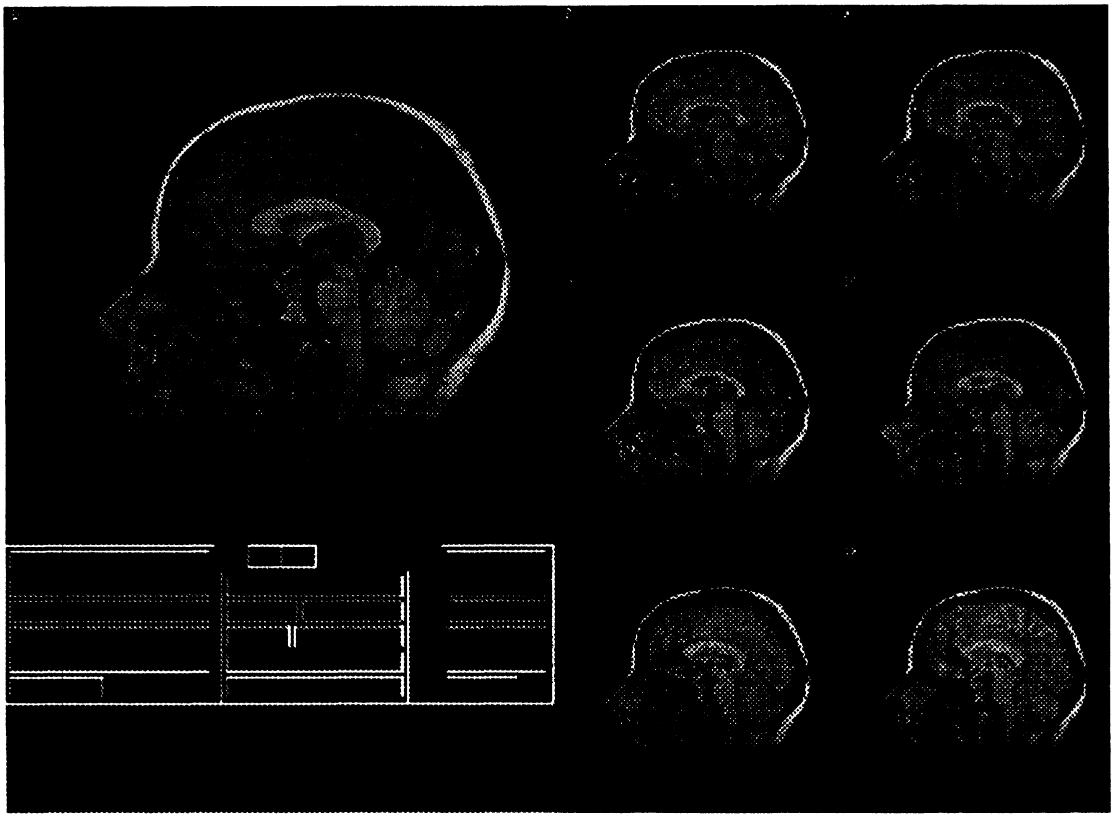

Figure 1. Magic Crayon interface. In this example the stacked display is on the top left and the mosaic display is on the right. The configuration of the different views is under user control.

We have implemented a prototype tool toward this goal of a linked rapid object definition and 3D visualization. A prototype software program was developed by Tim Cullip of the UNC medical image presentation group that achieved 10 frames per second on a Silicon Graphics Reality Engine workstation. Brad Hemminger and Michael North of UNC Radiology have developed a software package, called SeeThru, based on this prototype [27]. SeeThru supports several current direct volume rendering methods (xray projection, maximum intensity projection, opacity-based blending, and Levoy-Style gradient based), and has an improved computer-human interaction allowing direct user control of all viewing and rendering parameters (figure 2). The interactive capacities of SeeThru have been found effective for visualizing complex anatomy during thoracic surgical planning.

5. REGION SELECTION TECHNIQUES

Hierarchy Interaction. Three methods of interacting with ridge flow or other 3D object-subobject hierarchies have been developed and integrated into the Magic Crayon. A *parent* function allows the radiologist to select a primitive region on one of the study's slices and then traverse up the hierarchy by adding larger and larger subtrees of 3D primitive regions. If the image hierarchy is correctly constructed, the subtree under an ancestor of the selected primitive region will define the 3D anatomical object (or a significant subregion) containing that primitive region. However anatomical objects often are made up of regions with varying density. Thus, even with a well-defined 3D object-subobject hierarchy, the user may have to select and grow multiple seed points requiring considerable time and interaction steps. The *global parent* is an augmented version of the parent operation. With this function, the user selects a set of seed points in one or more slices of the target anatomical object. On each application of the global Parent operation the system moves up the hierarchy one more level from each initial primitive region. A third *magic crayon* method (hence the tool's name as well) for using these object-subobject hierarchies envisions a tool all of us wish we had available as children trying to draw in coloring books. Such a magic crayon would have allowed us to scribble down the middle of an object, while the magic crayon neatly filled up to the borders but not beyond them. By holding the mouse button down and scribbling across the center of the 3D anatomical object, our "magic crayon" allows the user to select 3D primitive regions (or subtrees further up the hierarchy) rather than individual points. A single "region scribble" can select points across density regions, reducing the amount of human interaction required relative to the single primitive-region method. In addition to the magic crayon, there is a *magic eraser* that removes subtrees at a hierarchy level specified by the user.

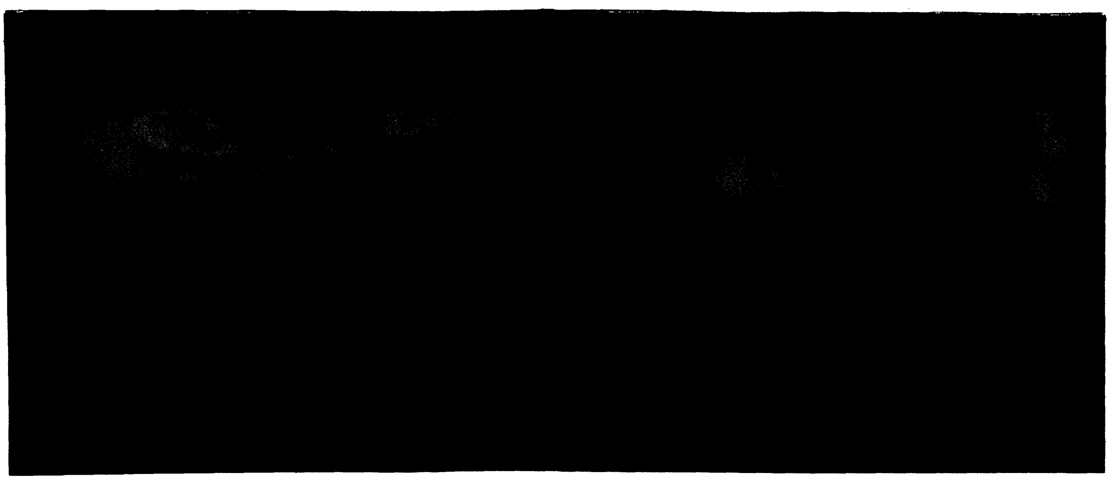

Figure 2. Two visualizations of a 3D Abdominal Spiral CT study with oral and intravenous to rule out pancreatitis using the UNC SeeThru tool are shown; the images are inverted. The image on the left has been interactively classified to show the outside surface information of organs and vessels. The image on the right shows a different classification of the same study depicting the renal vessels of interest.

6. PRELIMINARY RESULTS and DISCUSSION

Pilot work has been conducted to provided an initial evaluation of the speed and accuracy potential of the ridge-flow/magic crayon combination. A 3D brain stem, visualized on a MR head study can be defined in about 30 seconds. Kidneys and other anatomical objects provide similar results. Such objects typically take a trained technologist from 3 to 10 minutes to define using thresholding, auto contouring, size-limited seed fill, and hand contouring.

The accuracy shown in figure 1 is typical of what the current version of ridge-flow and magic crayon can generate and is as good as all but the most precise hand contouring with the defined edge typically being two or three voxels outside the sensible edge of the object. This is sufficient for most 3D surgery planning tasks, for radiation oncology 3D treatment planning, and even for many volume calculations tasks. However, there are many volume calculation tasks that may need even more precision. We believe that the current accuracy of ridge-flow is limited by our use of Gaussian blurring. Gaussian blurring is a linear process which typically averages object information with background data when applied near an object boundary. A better blurring method is needed which is sensitive to boundaries and will not average across them. Dr. Whitaker, a recent UNC Ph.D. graduate, has developed a variation of variable conductance diffusion [19] which, with modification, is being incorporated into ridge flow for improved behavior near object boundaries. We also plan to explore the use of preprocessed edge enhancements to sharpen the edges and thus better preserve the precise boundary during the ridge-flow process. We expect that these changes will allow ridge-flow to provide more than sufficient accuracy for clinically useful volume calculation.

We believe that the new methods we propose to develop will provide significantly better object definition for many anatomical objects. However, it is too much to hope that any single object definition method will work best with all classes of anatomical objects. Thus, the ideal object definition tool will likely consist of a hybrid of two more of these methods which together form a spanning set covering the four classes of anatomical objects. If this hybrid method is encapsulated into a well-designed interaction, this should provide a viable tool for rapid object definition during 3D treatment planning. Further, by combining the better features of these various methods, we plan to develop a completely new object definition method that is superior to any of the existing ones for a wide variety of anatomical objects.

7. ACKNOWLEDGMENTS

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