3D VISUALIZATION AND SEGMENTATION OF BRAIN MRI DATA

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Abstract: Automatic segmentation of brain MRI data usually leaves some segmentation errors behind that are to be subsequently removed interactively using computer graphics tools. This interactive removal is normally performed by operating on individual 2D slices. It is very tedious and still leaves some segmentation errors which are not visible on the slices. We have proposed to perform a novel 3D interactive correction of brain segmentation errors introduced by the fully automatic segmentation algorithms. We have developed the tool which is based on a 3D semi-automatic propagation algorithm. The paper describes the implementation principles of the proposed tool and illustrates its application.

1 INTRODUCTION

Magnetic Resonance Imaging (MRI) is mainly used to visualize the structure and function of the body. It is a method for sampling densities in a volume which provides detailed images of the body in any plane. Each point on an MRI scan corresponds to a certain point in the body being scanned. Though 3D coordinates of the point are directly available, it can be a problem to determine what organ the point belongs to. The process of establishing such relations between the MRI points and their origins is called *segmentation.*

All segmentation approaches can be classified into two groups: *automatic* and *interactive*.

Automatic segmentation is a well attended area of research. It assumes that verification and error correction will be done after the results of the segmentation are obtained. There are different methods used for automatic segmentation. For example, a generic brain model is used in (Rohlfing and Maurer, 2005), with the toolkit presented in (Bazin, Pham et al., 2005). In (Ibrahim, John et al., 2006), statistical properties of different areas of the brain are proposed to be used to determine which voxels belong to it. Graph-cut algorithm, as described in (Boykov and Jolly, 2001), represents MRI as a graph and uses a minimum flow partitioning for segmentation.

Interactive segmentation involves direct guidance by the user during the segmentation process. For example, in (Hahn and Peitgen, 2003) and (Armstrong, Price et al., 2007) the user controls the flow of the segmentation as well as provides hints to obtain correct results. To detect the border of a certain segment, it is common to define an energy related to this surface and minimize this energy (Giraldi, Strauss et al., 2003). An initial configuration is usually defined interactively by the user, with an interactive minimization resulting in operations similar to Adobe Photoshop lasso tool, as it was, for example, implemented in (de Bruin, Dercksen et al., 2005) and (Falcao and Udupa, 2000). A complete extension using surfaces was described in (Yushkevich, Piven et al., 2006), where the interactively defined original surface evolves to the energy minimum. The energy minimization does not always give correct results, and the current works do not provide for methods to fine-tune the proposed segmentations.

The interactive methods do not assume any pre-existing segmentation. Hence, they are not suitable for correction of segmentations done by the automatic algorithms. The automatic brain segmentation algorithms, however, are quite robust, and even when they do produce an incorrect segmentation, it can usually be easily fixed. Therefore, the most efficient way to segment a large amount of data is to apply an automatic algorithm to the bulk of MRI data and then check and correct the results.

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To perform interactive segmentation, the user needs a visual feedback reflecting both the original data and the current segmentation to make a decision about its correctness. Typically, it is done by going through 2D slice images. There are several software tools commonly used for the interactive correction of the segmentation results (e.g., *http://www.slicer.org*, *http://www.3doctor.org*). They provide the user with some 2D tools to examine and fix segmented areas in 2D slices similar to the ones available in interactive image editors, such as lasso, erosion, and area propagation.

Even with the advanced 2D tools, the necessity to analyze and edit every slice in every MRI data set is a daunting task. While there exist 3D versions of segmentation corrections, presented in (Kang, Engelke et al., 2004), the user interaction is still limited there to 2D volume sections. Even though the 2D sections convey all the information without any ambiguity, some artefacts can be only seen on 3D views since they do not contribute significantly to each individual 2D slice.

There exist different approaches to 3D visualization of MRI data segmentations. Volumetric methods give a good overall picture of the data set, however they often appear to be confusing and lacking fine details. Surface rendering could be a good alternative to it but the brain surface is usually not directly available in the original 3D volume MRI data. Hence, a 3D visualization method suitable for interactive segmentation still poses a significant research and development challenge.

In Section 2, we discuss the main idea of our method and provide a description of the algorithms. In Section 3, we describe the developed interactive segmentation tool. In Section 4, we give examples of the tool application and provide the collected statistics proving the advantage of our method over the commonly used ones.

2 VISUALIZATION FOR INTERACTIVE SEGMENTATION

In this section we introduce our visualization method for interactive segmentation. Interactive segmentation places important restrictions on the required visualization techniques. For example, if interactive segmentation requires the user to have information on the extent of the currently segmented area, it is important to provide a comprehensive feedback from the process so that the user does not have to switch between different views to get a complete picture. Hints on where to look for the wrongly segmented areas are also important and they have to be properly detected and visualized. The focus of the visualization process has to be on conveying 3D information relevant to the segmentation. Therefore, we do not use standard ways of rendering 3D shape using lighting since it is important to allocate most of the color information to visualize density. Instead, we have used edge outlines for displaying 3D shape as it is shown in Figure 1.

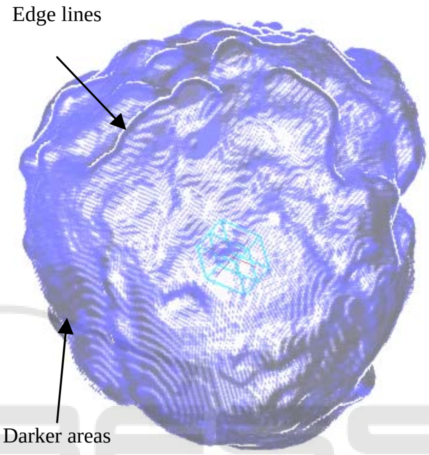


Figure 1: Rendering features.

2.1 Overview of the Proposed Interactive Segmentation Approach

Automatic segmentation algorithms are quite advanced and usually produce correct results. Even when they do fail, it usually results in a small problem which could be corrected interactively.

The task of interactive correction of the automatic segmentation has two parts: *error localization* and *error correction*.

Error localization is important as most of the segmentations are correct, and one has to find those which need to be edited. Current automatic segmentation methods do not provide the users with any hints on where to look for errors.

The proposed method is based on the error estimation of a particular segmented area, using both values from the MRI scan and the automatically generated 3D surface. The estimation is then used to provide a 3D view of the segmentation so that the user is provided with the hints on possible segmentation problems, as shown in Figure 2. The 3D view also reveals the defects which are difficult to identify using only 2D sections. The error hinting method is also used by the error correction algorithm which does not require a precise input from the user, i.e. the user just has to initiate and monitor the automatic detection process in a potential problematic error area.

Error correction can be still tedious, and the correction of wrong segmentations is different from doing segmentation from scratch. The automatic segmentation algorithms use different criteria to determine how each point of the volume should be classified. The failure of automatic classification means that the chosen criteria were insufficient to distinguish between the brain and non-brain tissues. Therefore, there can be defined additional distinguishing criteria, which, when combined together and aided by user interaction, provide us with the correct segmentation.

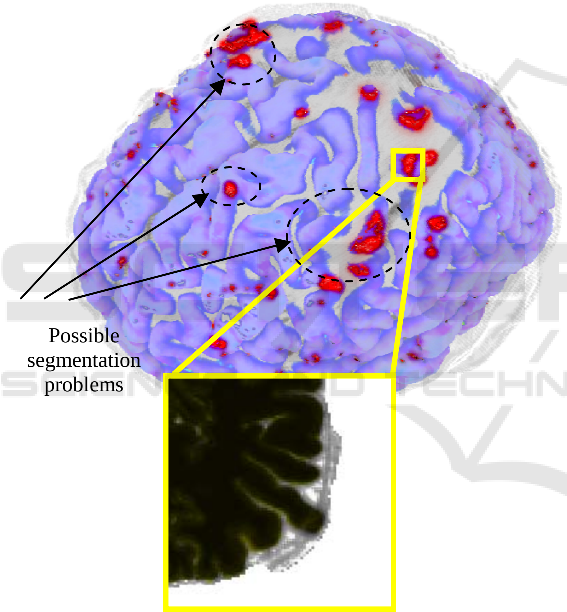


Figure 2: 3D MRI region and 2D plane section. Erroneous regions are highlighted.

3 METHOD DETAILS

The visualization and correction methods require information on whether a particular voxel is correct or not. There are different ways to estimate the probability that a given voxel is wrongly classified. Some of them are used in the automatic algorithms, and others are calculated during the interactive correction process.

For example, the conclusion about the correctness of segmentation can be based upon intensities of an MRI image and an automatically generated segmented surface and its normal vectors. The existing segmentation is produced by a fully automatic algorithm which is then gradually corrected.

The probability estimation is based on several *error criteria* dealing with a specific aspect of correctness estimation. The criteria are combined by a weighted average to produce the resulting estimation.

3.1 Error Criteria

To calculate an error criterion, one has to examine common artifacts produced by the automatic algorithm. Wrong segmentations are unlikely to be located far from the automatically generated surface of the brain. Also, they often appear disconnected from the properly segmented area. Finally, they usually consist of voxels with a similar intensity. As such we introduce the following criteria.

The *Depth* criterion assigns a smaller error probability to deeper voxels, as they are less likely to be erroneously segmented.

The *Topology* criterion checks whether there are disconnected parts in the segmentation. There are automatic algorithms which can mark small chunks of dura matter as belonging to the brain. The topology criterion is designed to mark such chunks as erroneous by analyzing the length of the line containing the point.

The *Intensity* criterion uses the user input and the intensity information. It exploits the fact that the most erroneous areas are of a similar intensity, as they are usually descended from the same tissue, e.g., skull, eye, etc.

To allow the user to guide the correction process, it is required to provide efficient feedback mechanisms. In our case, these are visualization methods tailored to displaying and highlighting the segmentation errors.

3.2 Visualization

All automatic segmentation errors in skull stripping happen on the generated surface of the brain. There is no point to overwhelm the user by displaying the internal parts of the segmented region. We just take the outer voxels and color them according to the respective error criteria, so that the user could determine the most likely problematic part.

If available, a white matter surface with segmentation error hints is visualized behind the transparent brain surface, as shown in Figure 2.

As shown in Figure 1, to create creases conveying 3D shapes when intensity is fully utilised for providing density information, we have used an extension of the point-based rendering method, so that the points located on the edges would let the background color be seen through by setting them to half-transparent, thus providing the outlines of 3D features. The intensity then is completely devoted to hinting the user on where the segmentation errors might have occurred.

In general, it is not always possible to calculate every criteria until the user selects a seed point. It is also not possible to set the seed point until all criteria are known, as there is no information to base the decision upon. We have solved this problem by providing the user with preliminary information, which can help to make the initial estimate by the user. As the user only sees the surface of the segmented area, it is impractical to use the direct intensity information of the surface voxels, as the surface is usually of a uniform intensity. Volume rendering would be redundant, as we only need information on the volume several layers deep. To provide an idea on internal structure without resorting to unnecessary volume rendering and requesting an input from the user, we propose to color each surface voxel with an average intensity of the surrounding segmented voxels. If there are abnormalities beyond the surface of the segmented area, they will be immediately noticeable as a surface intensity pattern.

If such averaging is not sufficient, it is also possible to visualize layers of voxels below the surface. By interactive changing the layer, the user can get valuable insights on the structure of the upper layers of the brain. Figure 3 shows results of the visualization by progressive layer removal.

Finally, quite often the surface of the currently segmented region is available. To help the user to locate the wrongly segmented areas, we have interleaved the surface with the point-based display and painted the surface with the probability criteria provided by the segmentation error criterion. As the surface of the brain is interpreted as a transition from the white to dura maters, it makes sense for the error criterion to analyze the sequence of voxels sorted by their proximity to the surface. An example of such sequences is shown in Figure 4.

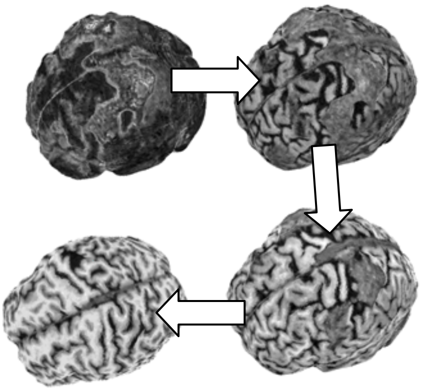


Figure 3: Progressive interactive layer removal provides information on the outer voxels layout.

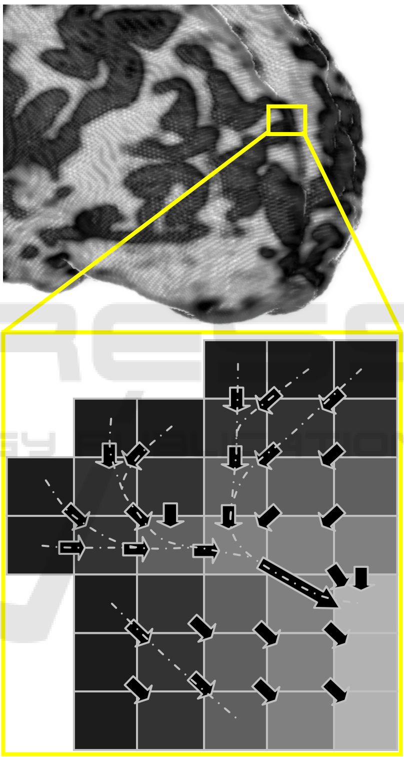


Figure 4: Depth map for defining the correctness metric. Gray levels denote the depth of a particular voxel. Arrows show the closest voxel from the next level.

Another promising approach to generate hints for the wrongly segmented locations is to use the white matter surface and analyze the MRI values along the normals (Figure 5). From our experience, the users who have tried this feature found it to be very useful and generally better and more efficient than the method of scanning every slice for possible defects.

While we avoid volume rendering, the seeds placed by the user can be located beneath the surface of the segmented area. Therefore, it is necessary to provide an ability to make the surface display transparent. Once the user suspects a region to be wrongly segmented, it is required that there must be an easy access to the original 2D MRI data slices for verification.

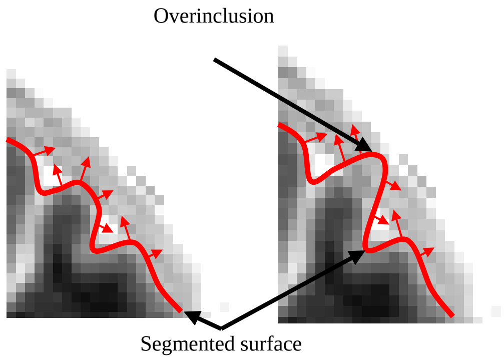


Figure 5: Segmentation error hint generation by analyzing the intensity changes along normal vectors.

4 APPLICATION

To construct an application, one has to define input data, consider how to arrange the software components and, finally, define how the software would fit into the general workflow.

4.1 Source Data

The interactive segmentation process starts with the result of a fully automatic processing. For example, it is quite common to have about 50 incorrectly skull-stripped images out of 300 which can be concluded by an expert. The automatic skull stripping algorithms are tuned to avoid classification of voxels belonging to the brain as non-brain ones, i.e. to avoid false negatives. Therefore, all segmentation errors are essentially non-brain tissues wrongly classified as belonging to the brain. An example of such a misclassification is shown in Figure 6, where all the displayed voxels were classified as the brain, while the lighter part on the left does not belong to the brain.

Our goal is to improve and speed up the interactive correction. We are using the proposed propagation method and functions for propagation to create a robust interactive segmentation correction tool which is more efficient than a 3D slicer for the second processing step.

4.2 Application Workflow

As described in the previous section, the segmentation consists of 2 steps: model examination and model correction. A pure 3D display is still insufficient for the conclusive assessment of the segmentation since we only display the surface and the selected voxels. To help the users navigate through the volume, a 2D section display is also provided as shown in Figure 7. The sections are continuously updated while the cursor is being moved across the volume, so that the user can better understand the internal structure of the volume to apply the interactive operations to it.

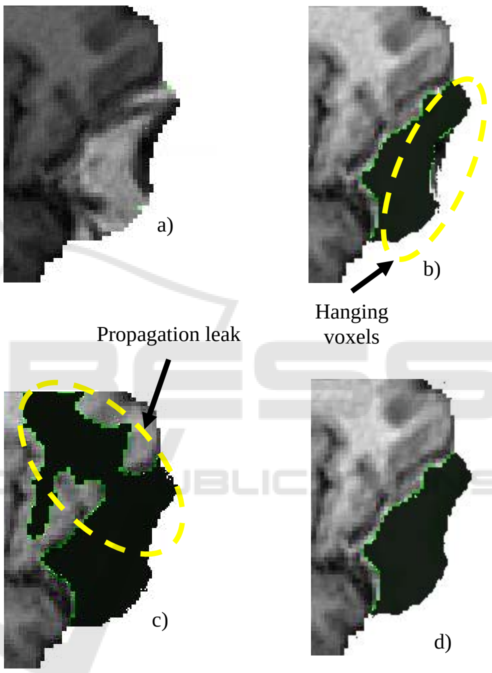
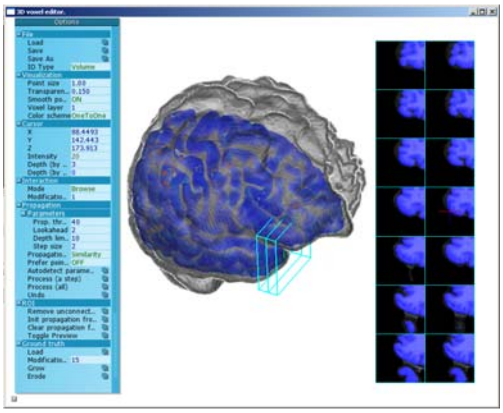


Figure 6: Error correction problems. a) Original, uncorrected segmentation error. b) Error corrected using intensity criterion alone. Note the hanging voxels. c) Topology is taken into account, but leaks occur. d) Proper error correction.

The automatic skull stripping requires a lot of processing power and it runs without supervision. It produces hundreds of images, which should be checked for correctness. The improved workflow of the interactive checking and correcting skull-stripped volumes is organized into the following steps, repeated for every MRI scan produced:



3D voxel editor.

Options

File
Load
Save
Save As
3D Type Volume

Visualization
Point size 1.00
Transparen... 0.150
Smooth po... ON
Voxel layer 1
Color scheme OneToOne

Cursor
X 88.4493
Y 142.443
Z 173.913
Intensity 20
Depth (by ... 3
Depth (by ... 0

Interaction
Mode Browse
Modificatio... 1

Propagation
Parameters
Prop. thr... 40
Lookahead 2
Depth lim... 10
Step size 2
Propagatio... Similarity
Prefer poin... OFF
Autodetect parame...
Process (a step)
Process (all)
Undo

ROI
Remove unconnect...
Init propagation fro...
Clear propagation f...
Toggle Preview

Ground truth
Load
Modificatio... 15
Grow
Erode

Figure 7: Application interface.

1. An MRI scan is loaded into the application and the user can see the 3D surface of the brain colored according to the average intensity of the voxels located close to the surface.
2. A 3D surface generated by the automatic approach is loaded and analyzed to highlight the most probable problematic areas.
3. The user examines the pattern and scans suspicious areas with the 2D section tool. If the area indeed contains a segmentation error, the user places a seed point there, using either the 3D or the 2D section view.
4. Once one or a few seed points are selected, the user initiates the propagation process, which automatically attempts to select points similar to the seed points. The automatically selected points are prominently displayed with a different color. The user monitors the process using the 2D section view or the 3D transparent view, and constantly checks that only invalid voxels are selected. At any moment, the propagation can be smoothly reverted.

The automatic process ceases when all further propagations select only the valid voxels. The user then removes all the automatically selected voxels and scans for more segmentation errors to correct. If the user realizes that some valid voxels are removed, they can be recovered with the multilevel undo function.

The erosion tool removes a layer of topmost voxels from the mask in a selected location. The operation can be repeated until the desired result is obtained, as shown in Figure 8.

When the processing of the current data is completed, it is saved in the same format as the original data, and the next one is loaded into the program.

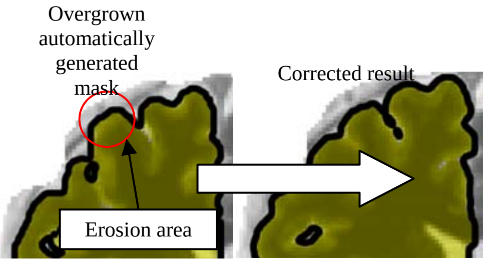


Figure 8: Segmentation erosion.

An overview of the application workflow diagram is given in Figure 9.

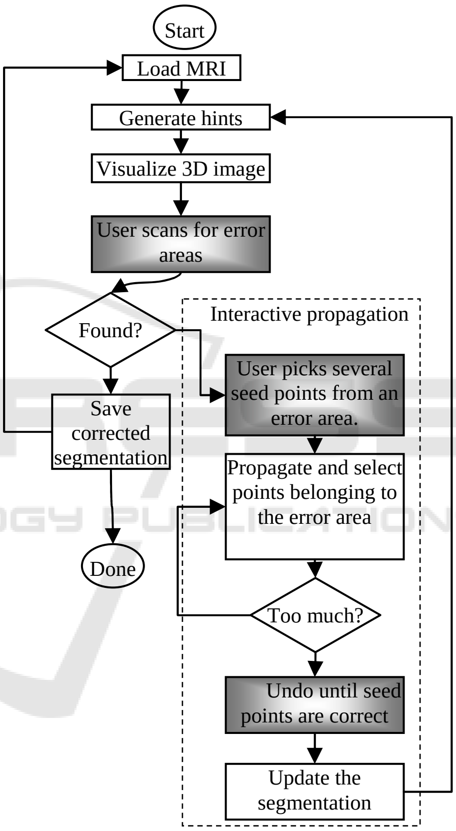

Start
Load MRI
Generate hints
Visualize 3D image
User scans for error areas
Found?
Interactive propagation
User picks several seed points from an error area.
Save corrected segmentation
Propagate and select points belonging to the error area
Done
Too much?
Undo until seed points are correct
Update the segmentation

Figure 9: Application workflow diagram.

Figure 10 shows 2D sections illustrating an interactive session where a wrongly classified area was corrected using the developed interactive semi-automatic software tool.

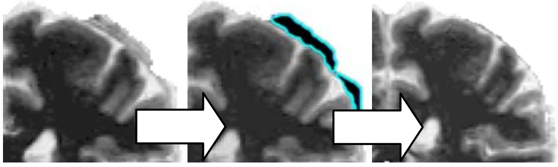


Figure 10: The result of correction.

4.3 Software Components

To provide the described workflow, the following modules were required:

File I/O, for reading/writing MRI data, for loading data to the volume storage, and writing data as requested by the interface module

Interface module is based on a common library, it provides OpenGL facilities, and processes keyboard and mouse input.

Rendering module takes data from the volume and point set storages and presents it to the user in a predefined manner, according to the current cursor position and camera orientation.

Volume storage tracks information on the current state of the MRI image. It also stores volume undo information.

Surface storage keeps track of a surface generated by the automatic algorithm. It uses normal criteria to determine where the automatic algorithm failed.

Point set storage efficiently stores current selection, surface points and colors, and it is a basis for propagation.

Error criteria modules include *depth*, *topology*, *surface* and *intensity*, for using in criteria evaluation as described in Section 3.

Propagation module uses error criteria to gradually change the point storage according to the error criteria. Once instructed by the interface module, it can perform undo, as well as application of the current point set to the volume.

The module diagram of the application is shown in Figure 11.

4.4 Performance

To judge about the success of a new segmentation method, one has to compare its performance with a traditional way of correcting the mistakes of automatic algorithms.

Let us consider the defect shown in Figure 7. It spans over 50 slices. Each slice takes around 10-15 sec to correct, which amounts to around 10-15 minutes per MRI file. Given 50 erroneous images per batch, it would take more than 10 hours to correct one batch. Our approach requires from the operator on average 2 minutes to locate and remove a similar defect, as illustrated in Figure 12.

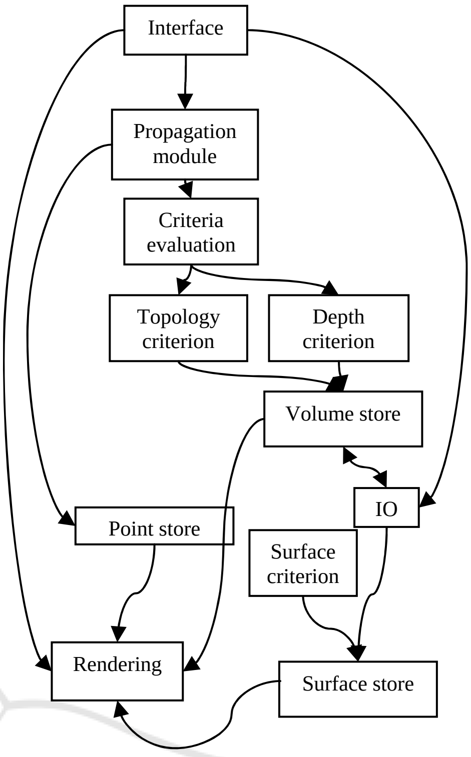


Figure 11: Application modules.

Therefore, it provides an estimated 5-fold productivity increase for the correction phase. Extending the software to handle different segmentation tasks would save even more time.

In some cases, initial automatic segmentation of white matter has only slight defects which are easier to correct than the mask itself. While we can correct such minor voxel misclassification, it is still necessary to remove non-brain voxels from the mask in order to run the white matter surface estimation algorithms reliably. We can replace the interactive mask correction process with the combined correction of the white and grey matters segmentation, and then use the segmentation to obtain the mask for the second automatic segmentation run.

4.5 Implementation Platform

We have used C++ and OpenGL library for all the rendering required in the project. The modular code base with clearly abstracted platform-specific modules allowed us to make the software cross-platform, equally well supported on MACOSX, Linux and Windows.

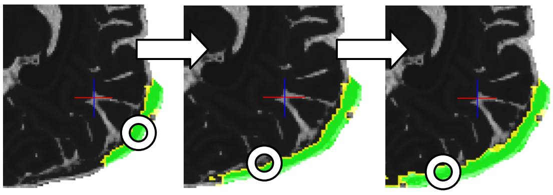


Figure 12: Interactive 3D control over segmentation process. Circle shows where interactive focus point is located.

5 CONCLUSIONS

Novel visualization algorithms developed specifically for segmentation purposes have been proposed along with a method for 3D interactive correction of brain segmentation errors introduced by the fully automatic segmentation algorithms. We have developed the tool which is based on a 3D semi-automatic propagation algorithm.

3D visualization of the misclassification hints allows the user to focus attention on the problematic areas and avoid working with individual slices where it is not necessary.

The proposed semi-automatic method uses a controlled propagation and allows for an efficient correction of the segmentation errors. The proposed software modules layout for the new interactive segmentation and visualization methods will allow for efficient development of advanced segmentation tools in further research and improvement of the initial software.

We have also proposed an efficient method for hinting the user where a segmentation error might occur. This is done by averaging several layers of the image closest to the surface. This method is simple to implement and provides satisfactory results however it has high failure ratio and has to be replaced with a more robust approach.

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