Efficient Brain MRI Segmentation for 3D Printing Applications

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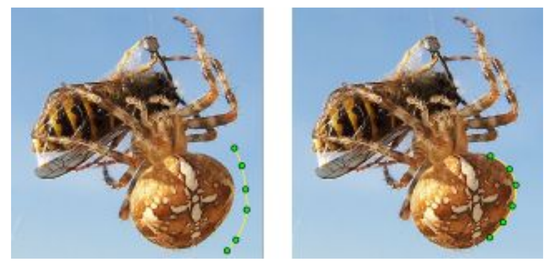
Background

Motivation

- Brain folding governed by thin plate mechanics [2]
- MRI segmentation useful for finite element simulation, 3D printing [4]
- Applications to neurosurgery, injury simulation [4]
- Segmentation remains bottleneck in this workflow: requires ~1 day of work even with expensive software
- Goal: create algorithm for fast brain MRI segmentation

Previous Work

- Previous segmentation methods based on statistics, edge detection, energy minimization [1] [5] [7]
- Active contour methods very promising – natural connection to brain folding mechanics [2] [4]
- 3D printing applications almost entirely unexplored



Active contours fit spline to contour with minimal energy [3]

Mathematical Framework

Active Contour Model

- Brain mechanics governed by:

$$\frac{E_c}{1-\nu_c^2}\frac{t_c^4}{12}\frac{d^4v}{ds^4}+Pt_c\frac{d^2v}{ds^2}=q$$

- Treat contour as zero level set: $v(s) = \{(x,y) \mid \varphi(t = 0,x,y) = 0\}$
- Evolve according to Hamilton-Jacobi equation: $\varphi_t = F|\nabla\varphi|$
- This study used model from [3]:

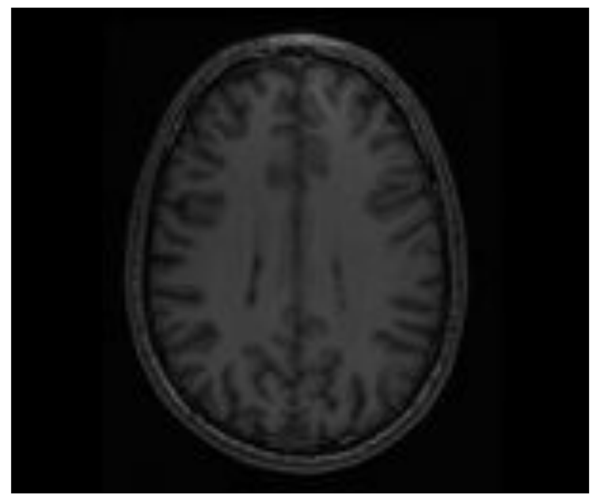
$$\frac{\partial\phi}{\partial t}=\delta_\epsilon(\phi)\left[\mu\,\mathrm{div}\left(\frac{\nabla\phi}{|\nabla\phi|}\right)-\nu-\lambda_1(u_0-c_1)^2+\lambda_2(u_0-c_2)^2)\right]=0$$

Brain Geometry

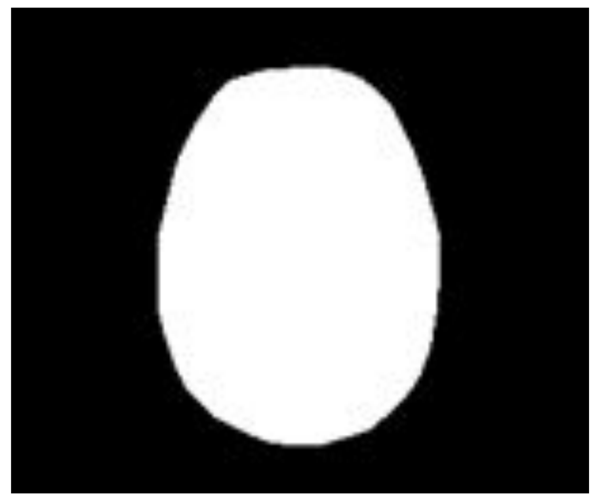
- Treat brain as 3D function $\psi(x,y,t)$
- Take $\psi(x,y,0)$ as thickest slice of brain MRI
- Define: $\Gamma(x,y)_i = \{\psi(x,y,t) \mid t=h \times i\}$, $i \in \mathbb{Z}$, h slice step size
- Take conv(supp $\Gamma(x,y)$) as convex hull of support of $\Gamma(x,y)$
- Then: conv(supp Γ_0) $\subseteq$ conv(supp $\Gamma_{\pm1}$) $\subseteq \cdots \subseteq$ conv(supp $\Gamma_{\pm n}$)
- Use convex hull of support of previous slice as initial guess to accelerate convergence

Experimental Results

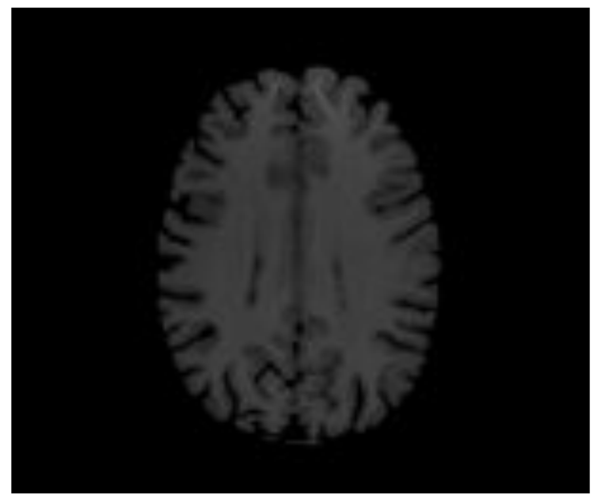
Image Processing Algorithm



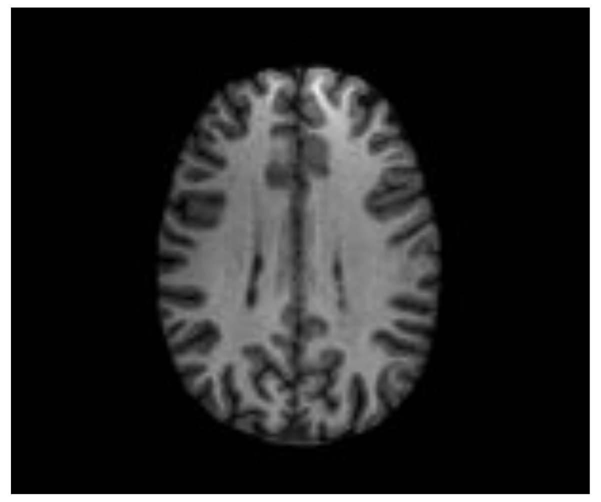
Original Slice from patient MRI



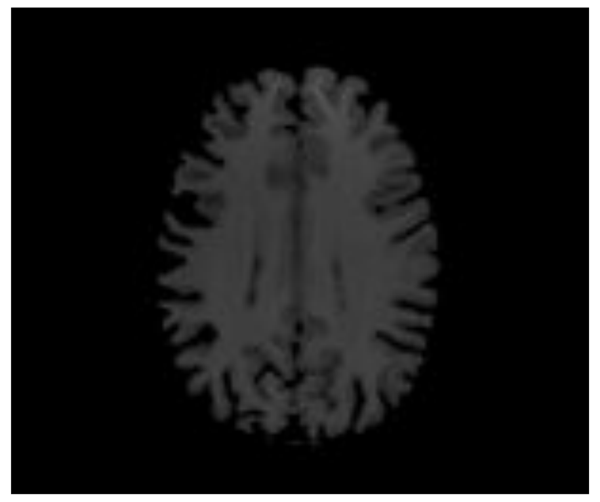
Convex hull of mask from previous slice



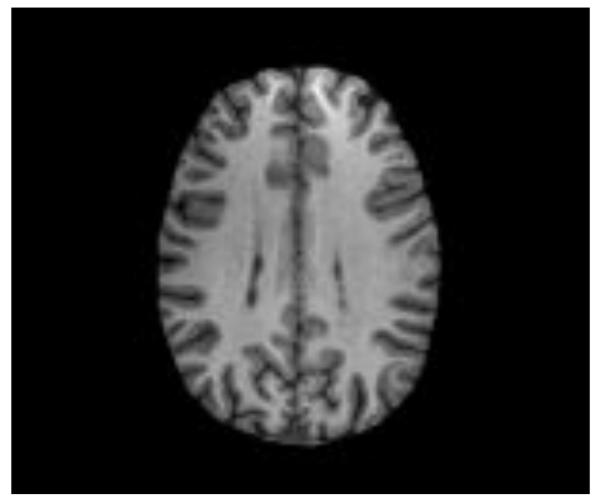
Step 1: Segment out brain portion using mask of previous slice



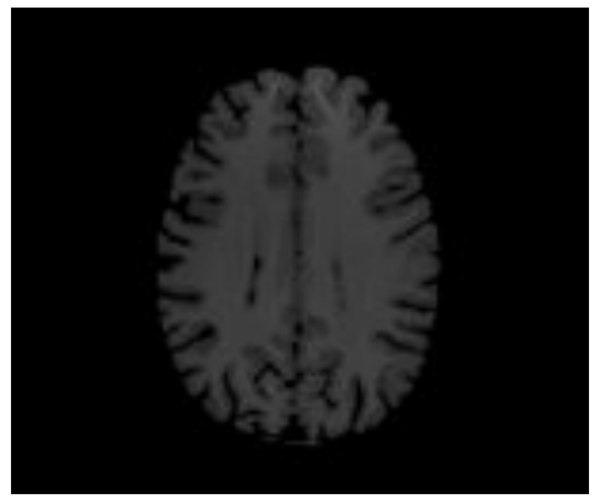
Step 2: Apply gamma filter (γ=2.0) to enhance white matter



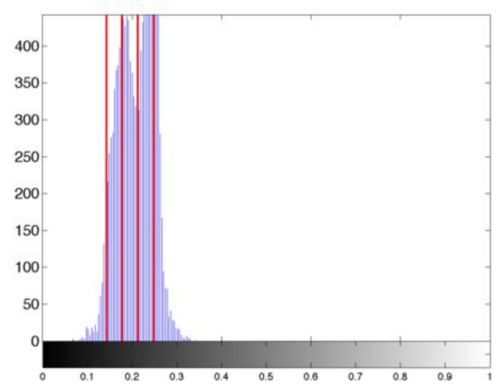
Step 3: Segment white matter via active contour, convex hull initial guess



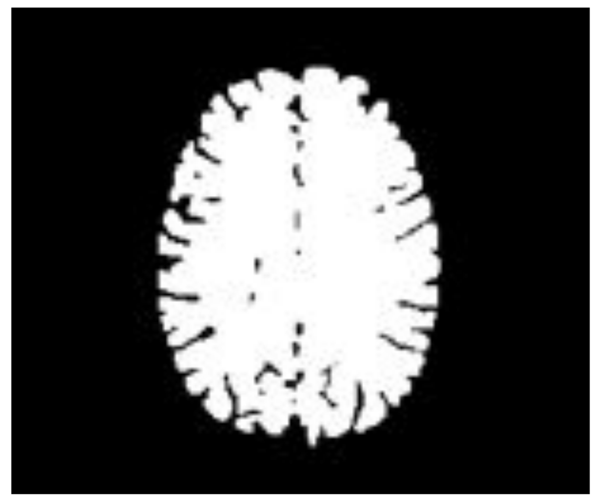
Step 4: Apply gamma filter (γ=1.5) to enhance all brain matter



Step 5: Segment with active contour, use white matter as initial guess



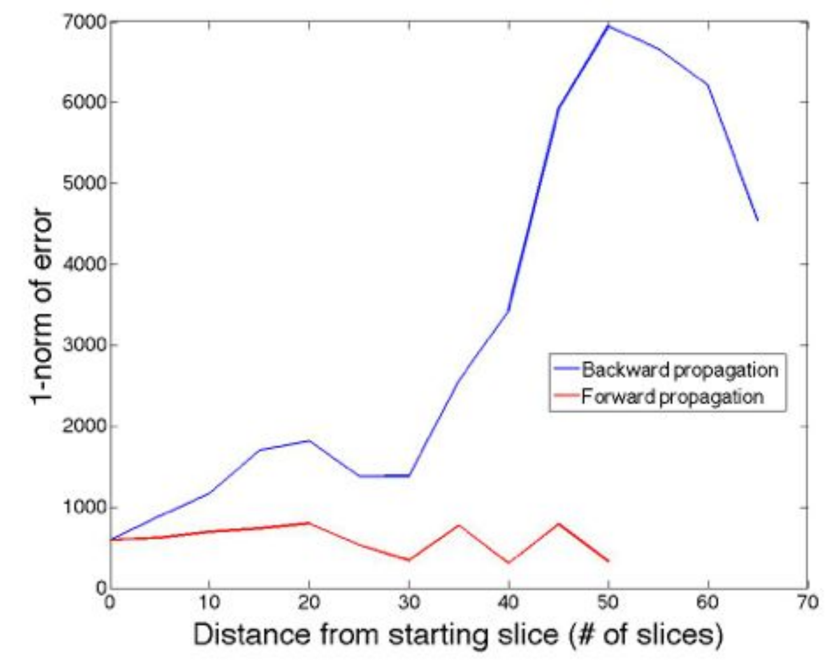
Step 6: Threshold with average minimum centroid with k-means clustering



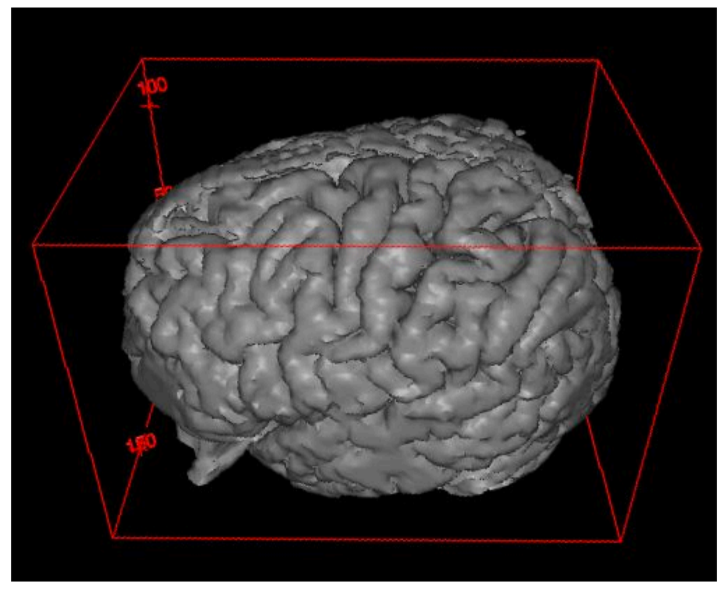
Step 7: Use morphological operations to post-process mask from step 6.

Results

- Error plot shows convergence worse at extremes of image sequence
- k-means effectively thresholds tissue missed by active contour segmentation
- Runtime in MATLAB with 2.6 GHz Intel Core i7 with 16 GB RAM 519 sec



3D Printing Results



Surface rendering of brain from segmented image sequence

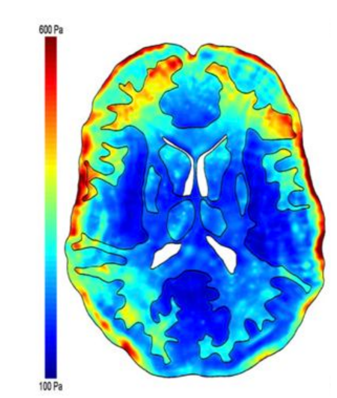
3D printed sample from surface rendering

- Surface rendered using marching cubes method
- Printed via fused deposition modeling

Conclusions

- Presented algorithm effective for extracting brain region
- Less effective at removing eyes, brain stem, meninges
- Nonlinear filtering increases effectiveness of active contours
- Morphological post-processing improves surface rendering
- Suitable segmentation for 3D printing applications

Future Work



FEM simulation of brain injury stresses, from [4]

- Improve accuracy for use in FEM mesh extraction
- Combine with statistical techniques to improve initial segmentation
- Improve backward propagation error via tissue-specific segmentation
- Further develop brain analogues

References

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