Automatic Brain Segmentation for 3D Printing

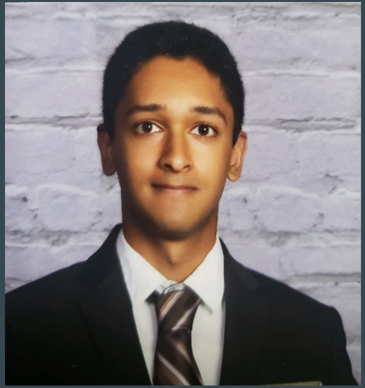
Group B1
Achira Fernandopulle, Bailey Gano, Leo Musacchia, Nathan Carpenter, Nicolas Re

Our Team

Mechanical Engineers

Bailey Gano
Parsippany, NJ

Nathan Carpenter
Westampton, NJ



Achira Fernandopulle
Livingston, NJ

Leo Musacchia
Dix Hills, NY

Nicolas Re
Bernardsville, NJ

Project Objective

Project Description

- Create a personalized brain model from an MRI scan
- Make the process from MRI scan to brain model nearly fully automatic

Business Model

- Print 3D model to help doctor/surgeons have a general visual aid when explaining the patient’s brain ailments or upcoming surgeries
- Create 3D models to serve as gifts/souvenirs for patients receiving brain-related treatment

State of the Art Review

- Currently only a small amount of highly trained professionals able to accurately model and 3D print the brain
- Limited amount of information or companies
- Majority of businesses with same idea sell on Etsy
    - Each with different material and program to reach the same outcome
    - Target different customers
    - All have the same flaw

Customer/Societal Needs

- Doctors are highly trained professionals
    - Must be able to effectively communicate to their patients
- Product will provide accurate model for doctor to reference
- Make information easier to understand
- Makes for a meaningful keepsake for patient

Stakeholders

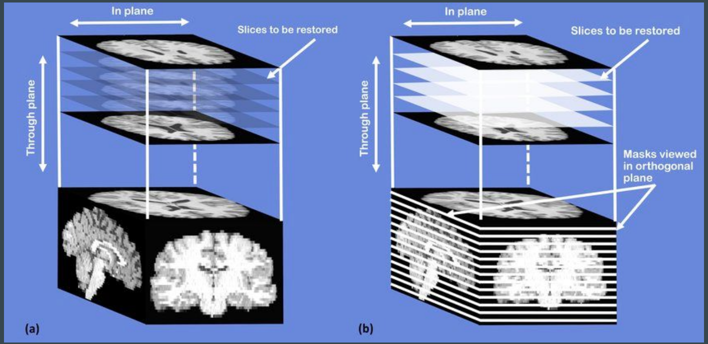
- Primary Stakeholders
  - Project Team: Achira Fernandopulle, Bailey Gano, Leo Musacchia, Nicolas Re Nathan Carpenter
  - Advisor: Johannes Weickenmeier
  - Senior Design Review Board
  - Target customers: Doctors, Nurses, Patients, Relatives of patients, enthusiasts
- Secondary Stakeholders
  - Supplier of materials
  - 3D Printer company
  - Software companies

Needs and Specifications

Index	Category	Need	Priority (1-5)
C1	Cost	Model is relatively inexpensive to make	5
D1	Design	Model is realistically sized	5
D2	Design	Model is durable	4
D3	Design	Model is aesthetically pleasing	1
D4	Design	Model is resistant to long term exposure to air	3
P1	Performance	Model is accurate enough to serve as general visual	5
S1	Safety	Model painted with non-toxic material	2

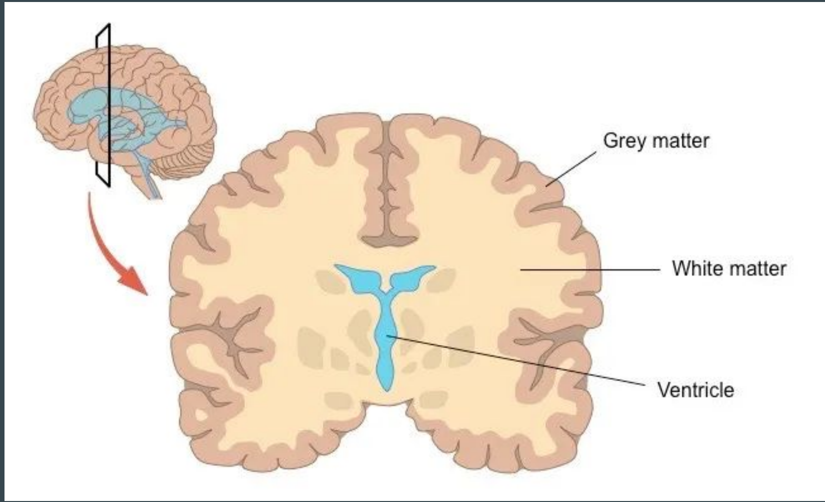
Technical Analysis - Gathering Input

- Medical images → stack of 2D images with in-plane and out-of plane resolution
- Medical MRI scanners typically take 20-60 minutes, have magnetic field strengths of 1.5 or 3T, and can reach resolutions of 1.5 x 1.5 x 4 mm^3
- Typical scans are isentropic with voxel dimensions of 3 x 3 x 3 mm^3
- Slice thickness: Diagnosis MRI thicknesses >2mm
- Want both in-plane and through-plane resolution to be as isentropic as possible



Technical Analysis - Material Analysis

- Finding a material to resemble brain matter is outside the scope of this project
- Final Material Decision:
  - Transparent PLA for grey matter
  - Opaque PLA for white matter
- Yield Strength = 60 MPa
- Tensile Modulus = 3600 MPa
- Flexibility Strength = 83 MPa
- Durable, strong, resistant to long term air exposure

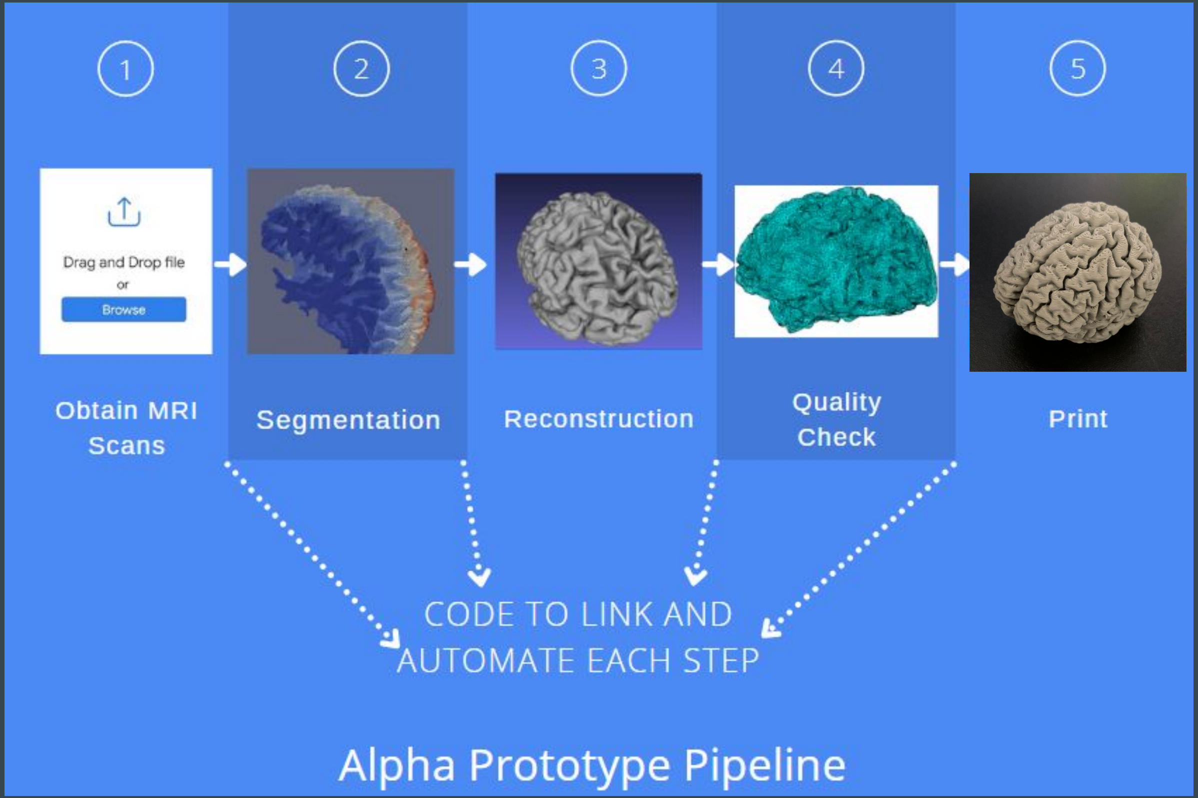


Technical Analysis - Cost Analysis

- PLA Density: 1.25 g/cm^3
- PLA Cost: 2 kg for \$50 → 2.5 cents per gram
- Adult human brain volume: 1260 cm^3
- $m = \rho V = 1.25 * 1260 = 1575$ g
- 1575 * 2.5 cents = \$39.38 ~ \$40 of filament per brain model

	As Students	**No Longer Students**
Filament Cost (per model)	\$40	\$40
MATLAB License Cost	\$0	\$2150
3D Printer Cost	\$0	\$3000
Total	\$40	\$5190 (\$5150 one time fee)

Engineering Design - Project Pipeline



Engineering Design

- The pipeline is designed to address critical points within the process and ensure a smooth flow and proper printed model
- Each step contains multiple functions that must be performed before moving onto the next
- The quality check step is key to blocking any faulty models from progressing through and allows us to repair the model if needed

Alpha Prototype - FreeSurfer Installation

- First step for our team to install FreeSurfer was to download the Ubuntu
  - The Ubuntu is a Windows subsystem for the Linux Operating system
- In the Ubuntu terminal, the following command was used to download Freesurfer
-
```
developer@DESKTOP-LD48TB7:~$ wget https://surfer.nmr.mgh.harvard.edu/pub/dist/freesurfer/dev/freesurfer_7-dev_amd64.deb
```
- The command below was inputted to update the necessary dependencies

```
developer@DESKTOP-LD48TB7:~$ sudo apt-get update
[sudo] password for developer:
```

- The following command was inputted to install FreeSurfer to the Ubuntu

```
developer@DESKTOP-LD48TB7:~$ sudo apt-get install ./freesurfer_7-dev_amd64.deb
```

- The 3 commands below are needed to set up the FreeSurfer's graphical user interface called Freeview

```
developer@DESKTOP-LD48TB7:~$ echo "export XDG_RUNTIME_DIR=$HOME/.xdg" >> $HOME/.bashrc
developer@DESKTOP-LD48TB7:~$ echo "export DISPLAY=:0" >> $HOME/.bashrc
developer@DESKTOP-LD48TB7:~$ echo "export FREESURFER_HOME=/usr/local/freesurfer/7-dev" >> $HOME/.bashrc
```

Alpha Prototype - Uploading NIFTI Files to FreeSurfer

- The subject directory must be opened so that the NIFTI File can be uploaded to the FreeSurfer GUI

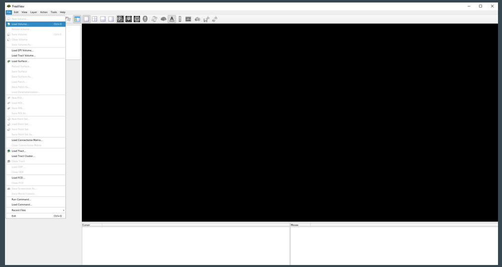
```
nathan@LAPTOP-FF9FC75L:~$ cd /usr/local/freesurfer/7-dev/subjects
nathan@LAPTOP-FF9FC75L:/usr/local/freesurfer/7-dev/subjects$
```

- Then the file is inputted into the subject directory by using the following command

```
nathan@LAPTOP-FF9FC75L:/usr/local/freesurfer/7-dev/subjects$
nathan@LAPTOP-FF9FC75L:/usr/local/freesurfer/7-dev/subjects$ sudo cp -r <Path to File> /usr/local/freesurfer/7-dev/subjects
```

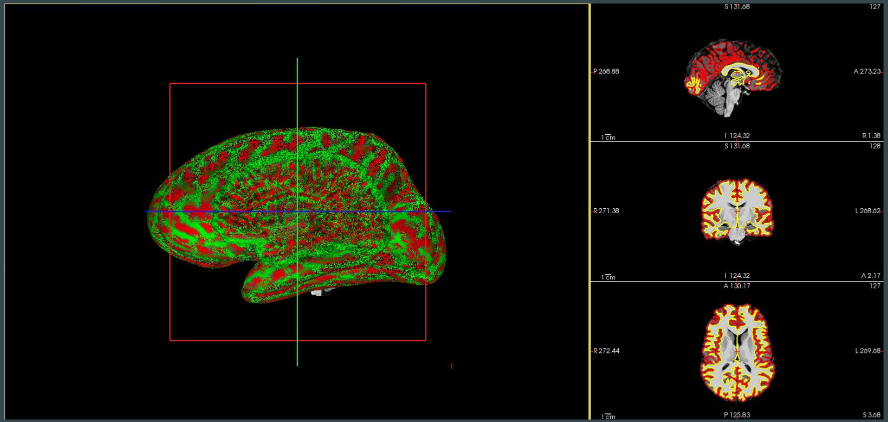
- Next, freeview must be opened so that the NIFTI File can be viewed after segmentation

```
nathan@LAPTOP-FF9FC75L:/usr/local/freesurfer/7-dev/subjects$ freeview
```



Alpha Prototype - Performing recon-all on MRI image

- The recon-all command was used to create all the necessary surfaces and volumes of the MRI image `recon-all -s subj01 -i subj1_anat.nii -all`
- In the command ‘subj01’ is the name found in the subject directory and ‘subj1_anat.nii’ is the file name
- This process took approximately 6 hours to complete
- Once the recon-all is complete, the volumes and surfaces seen below should be selected and observed to ensure that the quality is high



Alpha Prototype - Converting Surfaces to .STL Format

- The next step was converting the pial surface of the brain into an stl file that can be printed by using the commands below:

```
mris_convert /usr/local/freesurfer/subjects/mybrain/surf/rh.pial rh.stl
mris_convert /usr/local/freesurfer/subjects/mybrain/surf/lh.pial lh.stl
```

- The .stl format is compatible with 3D printers
- Once the .stl files were created they were exported to the computer's files
- The subject directory must be opened

```
nathan@LAPTOP-FF9FC75L:~$ cd /mnt/c/Users/cyntc/
```

- The command below was used to export the .stl files to our computer, and then the files were imported into MeshLab

```
nathan@LAPTOP-FF9FC75L:/mnt/c/Users/cyntc$ sudo cp -r /usr/local/freesurfer/7-dev/subjects/NIFTI01/surf/rh.stl /mnt/c/Users/cyntc
nathan@LAPTOP-FF9FC75L:/mnt/c/Users/cyntc$ sudo cp -r /usr/local/freesurfer/7-dev/subjects/NIFTI01/surf/lh.stl /mnt/c/Users/cyntc
```

Alpha Prototype - Enhancing the Model Using MeshLab

- The .stl files were imported into MeshLab to improve the quality
- The mesh was initially split into the left and right hemispheres
- Once the mesh was properly imported into MeshLab, it was improved using the following steps:
- The path below was used to fix layers of the brain segmented incorrectly

4. Filters>Mesh Layer>Flatten Visible Layers
5. Click Apply

- The following path was used to remove holes and overlaps that occurred in the model creation

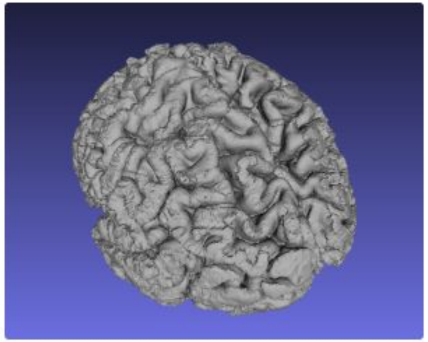
6. Filters>Remeshing Simplification and Reconstruction>Quadric Edge Collapse Decimation (this cuts out wholes and merges overlapping objects)
7. Enter desired Target Number of Faces (suggested: 200,000) and Apply

Alpha Prototype - continuing...

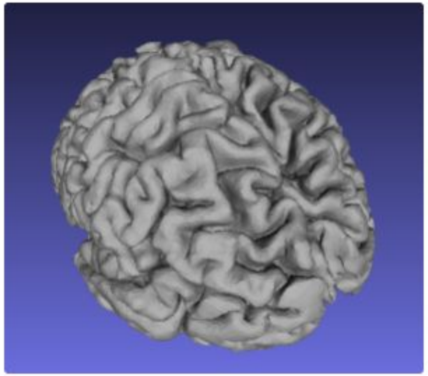
- The path below was used to smooth the surface of the model

  8. Optional: Filters>Smoothing, Fairing and Deformation>HC Laplacian Smooth (for esthetic reasons)

- Once all of these enhancements were made to the model, it was clear that the quality of the mesh was better



FreeSurfer output without corrections in Meshlab

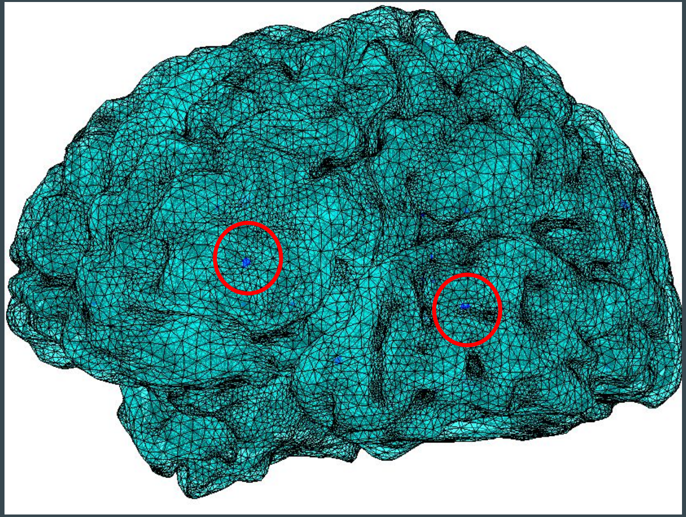


After corrections in Meshlab

Alpha Prototype - Quality Check/Repair

- Using stl file the model can then be uploaded into Matlab
- A mesh is then created for the brain in order for checks to be completed
  - Mesh quality is first checked in order to make sure each element is in an optimal shape
  - Aspect ratios are utilized to accomplish this check

```
StructuralModel = createpde('structural','static-solid');
brain = importGeometry(StructuralModel,'Brain.stl');
pdegplot(StructuralModel,'EdgeLabels','off')

mesh = generateMesh(StructuralModel,'Hmax',20, ...
                                        'Hmin',0.5);

Q = meshQuality(mesh);
elemIDs = find(Q < 0.3);

figure
pdemesh(mesh,'FaceAlpha',0.5)
hold on
pdemesh(mesh.Nodes,mesh.Elements(:,elemIDs), ...
        'FaceColor','blue','EdgeColor','blue')
```



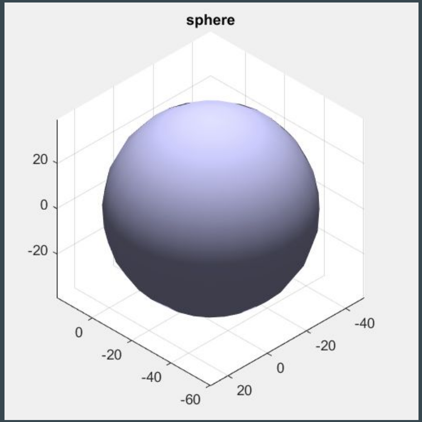
Alpha Prototype - Quality Check/Repair

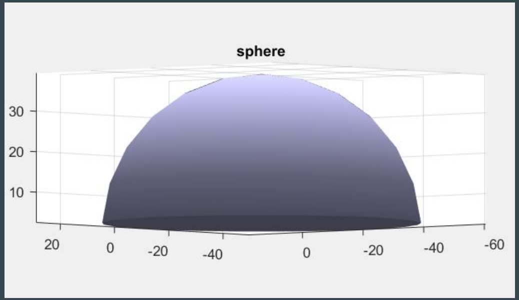
- Model now needs to be checked for holes and imperfections
- Algorithm shown below used to identify holes
    - Looks at each edge in the mesh and checks whether each has two triangles in common
    - If not, means that there is a hole or gap that needs to be filled

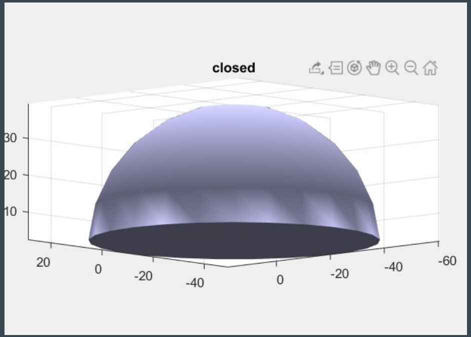
```
>> % MAKE a face/vertices structure
tmpvol = zeros(20,20,20);       % Empty voxel volume
tmpvol(8:12,8:12,5:15) = 1;     % Turn some voxels on
fv = isosurface(tmpvol, 0.99);

% REMOVE a face
fv.faces(30,:) = []; % Remove a face!

% TEST for gaps or holes
edges = sort(cat(1, fv.faces(:,1:2), fv.faces(:,2:3), fv.faces(:,[3 1])),2);
[unqEdges, ~, edgeNos] = unique(edges,'rows');
if size(edges,1) == size(unqEdges,1)*2
    % Every edge is used twice... consistent with a closed manifold mesh
    disp('No problem!')
else
    badEdgesMask = hist(edgeNos, 1:max(edgeNos))~=2;
    badEdgeNos = edgeNos(badEdgesMask);
    badNodeNos = edges(badEdgeNos,:);
    badFaceNos = find(sum(ismember(fv.faces, badNodeNos),2)>=2);
end
```

Alpha Prototype - Quality Check/Repair

- To fill in the holes, an stl modification package is used
    - Contains 4 key functions: GetVerts, AddVerts, DelVerts, and SlimVerts
    - Based on the vertices given by the hole finder, these functions can be used to fill in holes and imperfections
    - Code-intensive process: still being worked on to accurately work on complex models such as brains

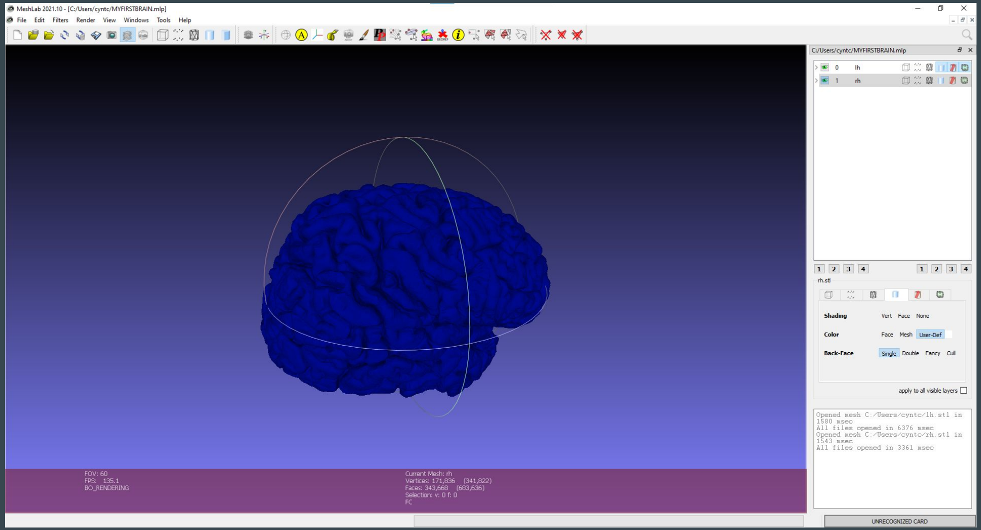


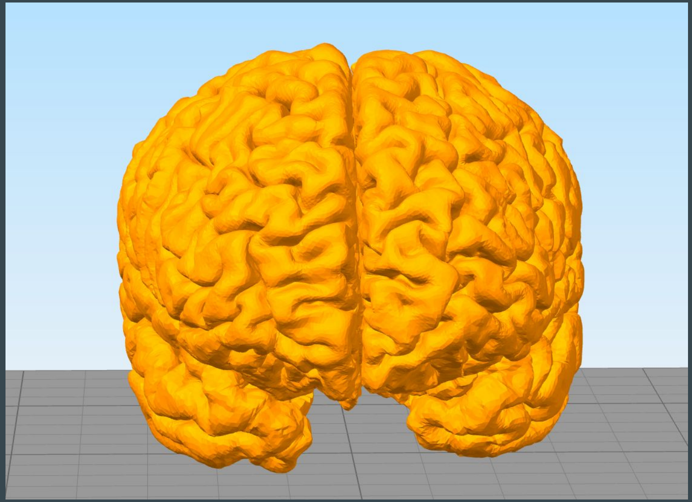




Alpha Prototype - Model Completion

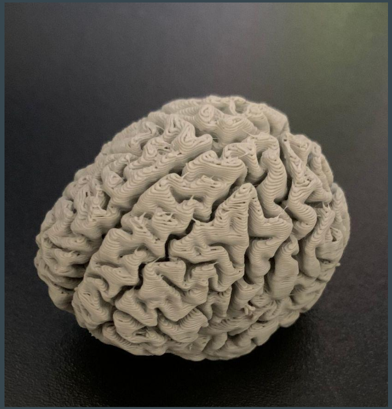
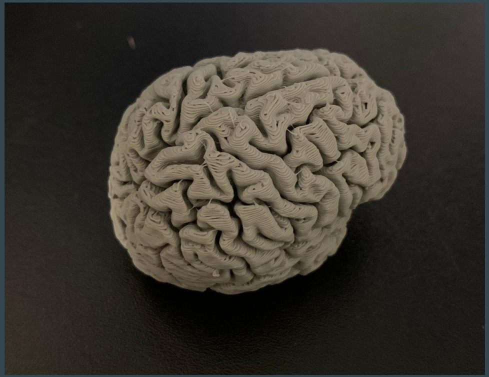
- Once the model was enhanced it was then analyzed to ensure that there were no imperfections
- Our team verified that the model exceeded our expectations and that the MeshLab modifications worked





Alpha Prototype - Printing

- Stl model was sliced and gcode was sent to the Proof Lab
- Planning on testing translucent PLA and other variants, but proof lab was having issues slicing and printing model (model takes 3-4 hours to print but took 2.5 weeks for the lab to print it)
    - Still divots and imperfections in the model that will need to be improved
- Showed that our process is viable and works, just needs quality improvements

Bill of Materials

BOM Item Number	Description	Vendor	Cost (each)	Quantity	Purchased	Received
1	Black PLA Filament (1 kg)	Micro Center	$15	2	No	No
2	Natural PLA Filament (1kg)	Micro Center	$19	2	No	No

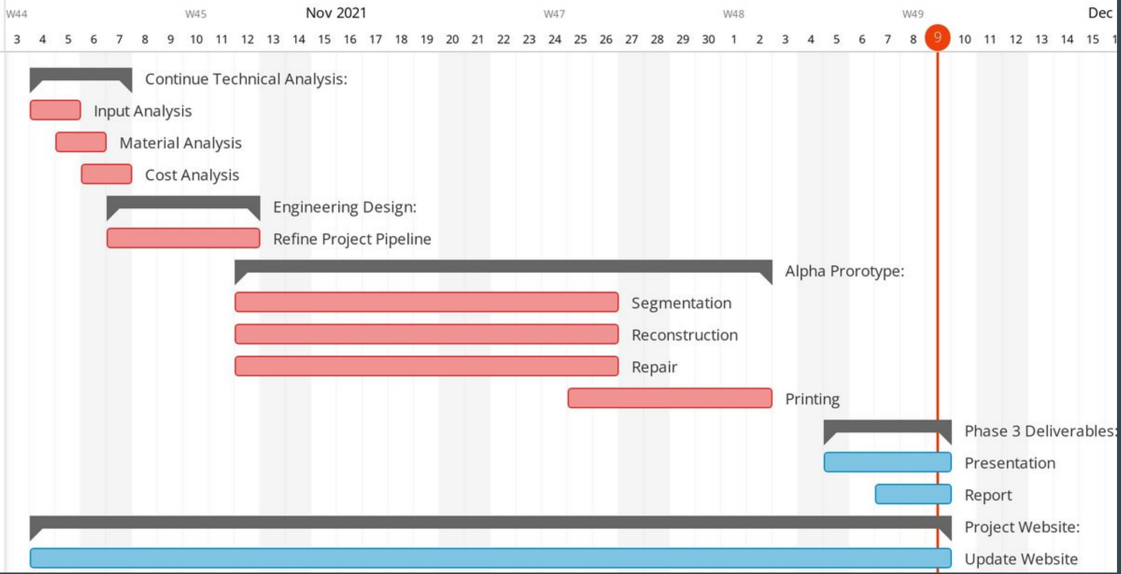
Updated Gantt Chart

Phase 3

Read-only view, generated on 09 Dec 2021

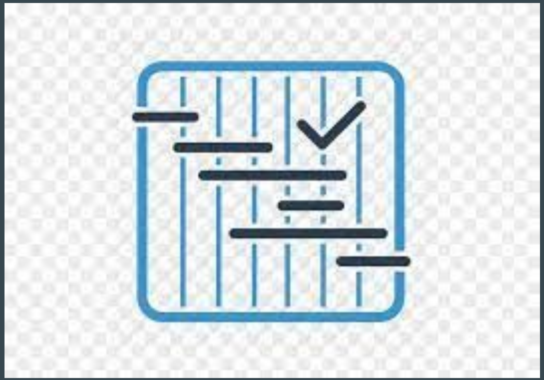
Instagantt

	ACTIVITIES	ASSIGNEE	EH	START	DUE	%
	Continue Technical Analysis:		-	04/Nov	07/Nov	0%
1	Input Analysis		-	04/Nov	05/Nov	0%
2	Material Analysis		-	05/Nov	06/Nov	0%
3	Cost Analysis		-	06/Nov	07/Nov	0%
	Engineering Design:		-	07/Nov	12/Nov	0%
5	Refine Project Pipeline		-	07/Nov	12/Nov	0%
	Alpha Prorotype:		-	12/Nov	02/Dec	0%
7	Segmentation		-	12/Nov	26/Nov	0%
8	Reconstruction		-	12/Nov	26/Nov	0%
9	Repair		-	12/Nov	26/Nov	0%
10	Printing		-	25/Nov	02/Dec	0%
	Phase 3 Deliverables:		-	05/Dec	09/Dec	0%
12	Presentation		-	05/Dec	09/Dec	0%
13	Report		-	07/Dec	09/Dec	0%
	Project Website:		-	04/Nov	09/Dec	0%
15	Update Website		-	04/Nov	09/Dec	0%



Project Plan

- Quality process code development
- 3D Print quality
  - Testing materials and mesh characteristics to enhance print
- User interface for MRI acquisition development
- Development of code to link steps and make process automated
  - Testing overall process with various different scans to see how they are handled



Thank You!