Automatic Brain Segmentation for 3D Printing

Phase 3 Report

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I pledge my honor that I have abided by the Stevens Honor System

Abstract

The project objective is to design and prototype an automatic process that converts MRI scans into 3D models that can be 3D printed into physical brain models. This report summarizes Phase 4, which includes the project statement and plan, testing and analysis of the alpha prototypes, and a final design and detailed fabrication plan for the beta prototype. The team began this phase by testing the alpha prototype in order to make sure that it is suitable to continue with for the beta prototype. While the alpha prototype focussed primarily on the programming used to generate, smooth, and print the models of the brain, the beta prototype will be much more focussed on connecting the steps of the original pipeline and creating a user interface for the customer to purchase the product. The following report will explain how the group plans to achieve this and an estimated timeline that details when each part of the project will be completed.

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<u>Project Statement</u>

Project Overview

One of, if not the most complex and least understood organs in the human body is the brain. This applies to both the doctors who must analyze imaging, diagnose issues, and, sometimes, perform surgery, and the patients who house the brains in question. Such complexity can form a disconnect of understanding between people who have gone through years and years of schooling on this subject and people who have not. The objective of this project is to bridge the gap formed between professional and patient through the use of a brain model personalized to each patient. This model will be an accurate representation to scale of the patient's brain that can be used by a healthcare professional to describe diagnoses, procedures, and any other possible areas of concern in a much more understandable and interactive manner. Another main objective of the prints are to serve as souvenirs given to patients by a practice or made available to people who have access to their scans and want a print of their brain. The pipeline that will be used to produce such a model goes as follows: take the MRI scan of the patient, run it through a segmentation software to form the model, clean up any possible holes or defects that may have occurred, convert that file into one that can be 3D printed, and then print it. In order to accomplish this task, the customer will interact with a user interface designed by the group. On the customer side, they will see an area to upload their MRI images and a progress bar to see where in the process the brain scan is. Behind the scenes, there will be a user interface for the employees to go through the actual pipeline as previously described.

Summary of Previous Work

As the second half of this project begins, it is important to highlight what work has been done in the first half in order to better understand how the project will progress through to the end of the semester. The primary focus of Phase 1 was to accomplish all of the preliminary tasks that would set the group up for success when creating an alpha prototype. This included a state-of-the-art review of similar products in order to get a gauge of what is already on the market regarding the scope of this project, any needs and specifications that must be met to have a desirable product, and the preliminary concept generation. This is where the first draft of the modeling pipeline was created that would be adapted and, eventually finalized, through the rest for the semester.

Phase 2 was spent doing a technical analysis for the project. This consisted of researching all of the possible programs that would be used to get from the MRI to a printable format. Some of the criteria that were strongly considered in order to choose each of these programs was ease of use, accuracy, processing time, and cost. All of these criteria were then put into a decision matrix and that was used to determine the programs that would be used in the alpha prototype. The softwares that were selected for each step in the pipeline are FreeSurfer for the segmentation, Meshlab for enhancing the model and converting it to an STL, and then the group decided to write a simple code to perform quality check on the model. There were also analyses done on the 3D printer that would be used and possible materials for the print.

Finally, in Phase 3, the group focused on solidifying the alpha prototype. Now that the software was chosen, they could be put in sequence and the team was able to fully go from an MRI scan to a 3D printed model. However, as with most alpha prototypes, there was much room for improvement. First, the group was only able to print a 1:4 scale model of the brain instead of a 1:1. Also, the customer will need some sort of user interface to interact with in order to purchase the product. And finally, further testing must be performed on the existing software to ensure a consistently accurate model. All of these points were addressed in Phase 4.

Goals and Objectives

The goals and objectives of this project have slightly changed since its onset to account for the work done in the previous phases and the amount of time left to complete it. The original plan was to create a fully automatic pipeline that would be able to take an MRI scan of the brain, convert it to an STL file after being fully segmented and smoothed, and send it to a 3D printer at the click of a button. This plan, however, disregarded a key portion of the project, which is the user interface. The group decided that the user interface would be more important to get completed than the full automation of the pipeline, so the focus will be shifted to that. Now, the objective is to create an interface for the customer to be able to purchase the brain model and send in their MRI scans, with a separate one for all of the back-end work that will actually put the MRI through the pipeline and send the printed model to the customer. This interface will present itself as a website or application and provide the customer with real-time progress on where their brain is in the process.

Feedback

One question that was received as feedback was why the brain needs to be personalized. A long term goal of the process is to produce brains with two materials and at a level of accuracy that can display the nuances of different people's brains. That would allow the physician to physically show a patient what is going on with them. The group is not at that point yet and the shorter term goal is to accomplish the automation process with the simple print in one material. Theoretically displaying abnormalities is possible, but an MRI with an abnormality has not been tested yet. This can still be accurate and unique to a patient's brain, but the main benefit that would come out of a simpler model that a physician would use is to build a stronger connection with the patient because the personalized brain can be meaningful to that patient.

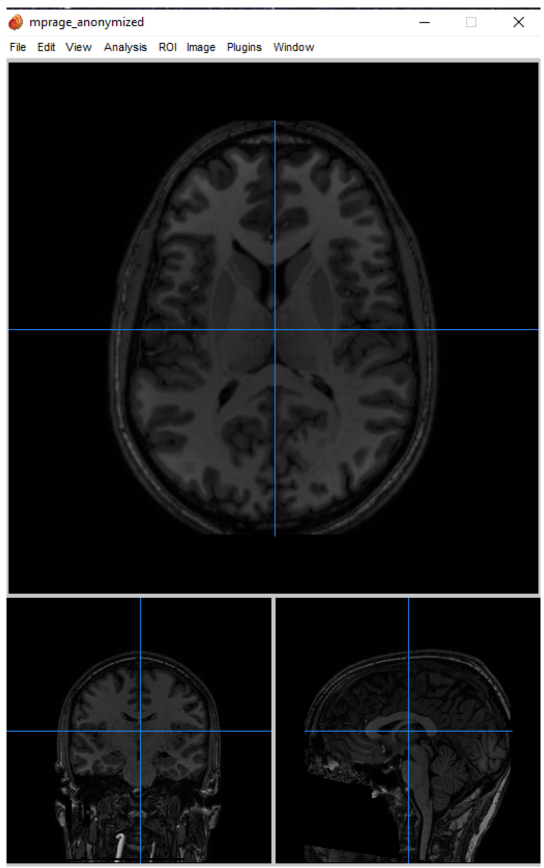
To address the feedback regarding how the automation process will be designed, the group has an ongoing design and has conducted research on how this will be accomplished. To bridge the gap between customer and pipeline process, a user interface design on a website is the first thing the group is going to tackle. Then the group can obtain a server and install the necessary softwares for the programs that are used onto that server. The website will allow the user to upload an MRI scan, send it to the server, and code written on the server will guide the file through each of the softwares to produce a printable file which can then be exported and sent to begin printing. Updates throughout the process are to be sent to the customer so that they are aware of the estimated time of completion.

One of the major concerns with the process is the long delay that takes place when printing the brain model. This step takes a long time due to the fact that the brain models are very complicated and the group is aiming for them to be as accurate as they can. In order for this to be achieved it takes a decent amount of time. Also currently the group is using the proof lab to print the models and some of the files get sent back and errors occur which delays the process even more. This goes along with the feedback about continuing to test different materials and print settings to try and figure out what generates the best model. With the challenges faced in the proof lab this has been difficult to accomplish. However the group currently has prints in process that should be finished in the coming week and the group has been working on finding other printers in labs to use to try and speed up the process. The benefit that the group has is that the code for the pipeline does not significantly change leading up to the print. Therefore, ongoing print testing can be conducted alongside the beta prototype development of the automatic pipeline for any further enhancements. In addressing the question about the brain model being printed hollow in order to reduce the print time and the amount of material needed, this is possible and is something that the group thought about doing however there were some structural issues that arose. The proof lab sent us a message saying that the printer received errors and could not execute this idea. Another question from the panel was whether the additional check after meshlab is essential. While it may not be needed in order to print the model it is something that the group wants to include as a precautionary step to make sure the model is one hundred percent ready to be printed so no unexpected issues or delays arise.

Design, Testing, and Evaluation of Alpha Prototype

Design

The alpha prototype for this project was mainly a proof of concept to determine if it was practically possible to use MRI scans of a brain to create a 3D printed model. For this reason, the design of the alpha prototype was a pipeline composed of open-source softwares that could be used to get from an MRI scan to a physical model. The first step in the pipeline was to segment the MRI scan using FreeSurfer. This process is done by performing Freesurfer's recon-all tool to segment the NIFTI file MRI scan.




```
recon-all -s subj01 -i subj1_anat.nii -all
```

Figure 1 : Command that segments the MRI image

MRI scans come in the form of many individual pictures that, when stacked together, form a cohesive brain model. FreeSurfer is only compatible with NIFTI formatted MRI files. The recon-all command is used to segment the brain scan layer by layer until all of the necessary surfaces and volumes have been created.

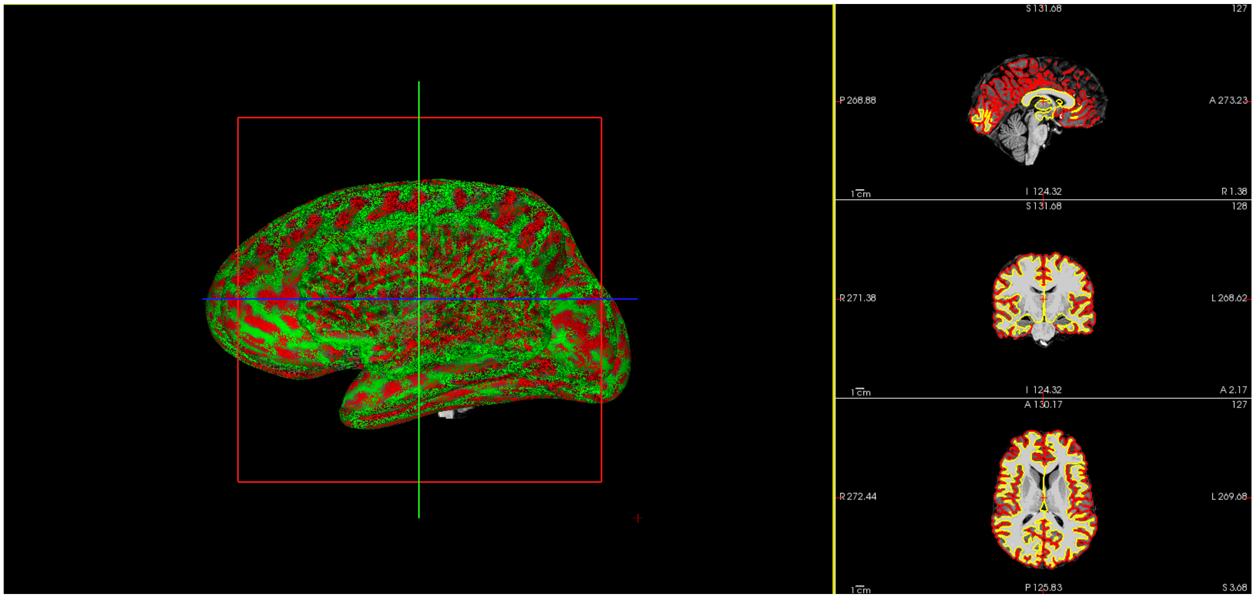
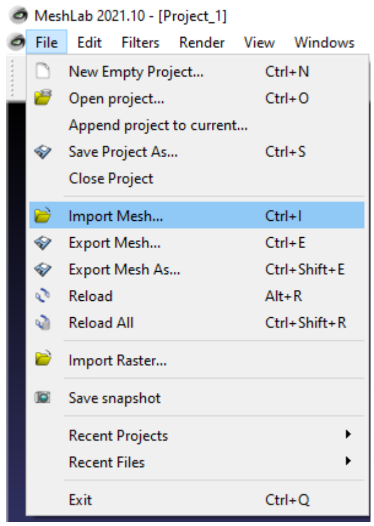


Figure 2: Inflated view of the model segmentation

Once the recon-all has been completed, the inflated view seen above is visible in the model view section of Freesurfer's graphical user interface. At this point, the inflated view is analyzed to ensure that it is high quality. Once this assessment has been made, there are two files that must be converted into the .stl file that is needed for printing. They are lh.pial and rh.pial. They are right and left hemispheres of the brain. These files are converted by using the following command:

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

Once these commands have been run, two .stl files are created. Once is for the right hemisphere, and the other .stl file is for the left. These two hemispheres can be combined by using another open source resource called Meshlab.The brain file can also be smoothed using Meshlab. Meshlab also creates a mesh around the surface of the image which can be used to find holes or other undesirable features that may have arisen during the segmentation process. There were a few critical steps used in Meshlab that enabled us to ensure the quality of our brain models will be consistently high.



First the team begins by importing the newly converted .stl files into Meshlab. Both the left and right hemisphere files must be imported individually. Once they have been imported correctly, the model can be saved which unifies the model into one .stl file.

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

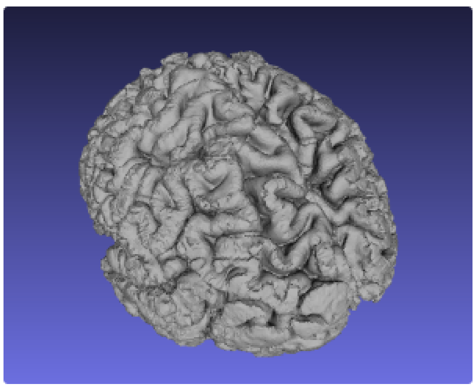
The first command that was used in Meshlab to improve the model quality was ‘Flatten Visible Layers’. This means that any layers that were segmented unevenly will be flattened. This will result in a much more accurate exterior.

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

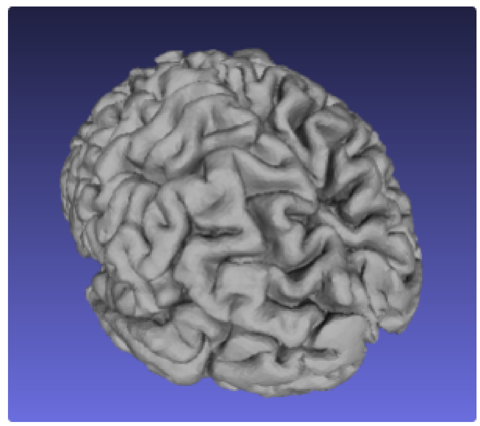
The next command that was input into Meshlab was Quadric Edge Collapse Decimation. This command is used to remove any holes that may have formed during the segmentation process. Also, if there are any overlapping edges, this command will remove them so that the model appears as it is intended to. The number of faces and vertices can also be manipulated by Quadric Edge Collapse Decimation. Altering the number of faces and vertices removes any excess materials. It allows the model to be simplified to its intended state.

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

HC Laplacian Smooth is a command in Meshlab that is used to smooth the pial or exterior surface of the model. It doesn't change the structure of the segmented model. However, even without altering the vertices or edges, this command is able to smooth any imperfections that remain after the completion of the first two steps.



FreeSurfer output without corrections in Meshlab



After corrections in Meshlab

Figure 3: Before (left) and after (right) MeshLab alteration

Completing the three steps listed above will ultimately make the improvements seen in the model above. These improvements are very noticeable and allow the team to provide a high level of quality control. This makes the product much more reliable, and customers will be able to depend on us for a consistent product due to our alterations made in MeshLab. It was very important to our group to be able to show that we had control over the quality level of our models. MeshLab has allowed us to do exactly that.

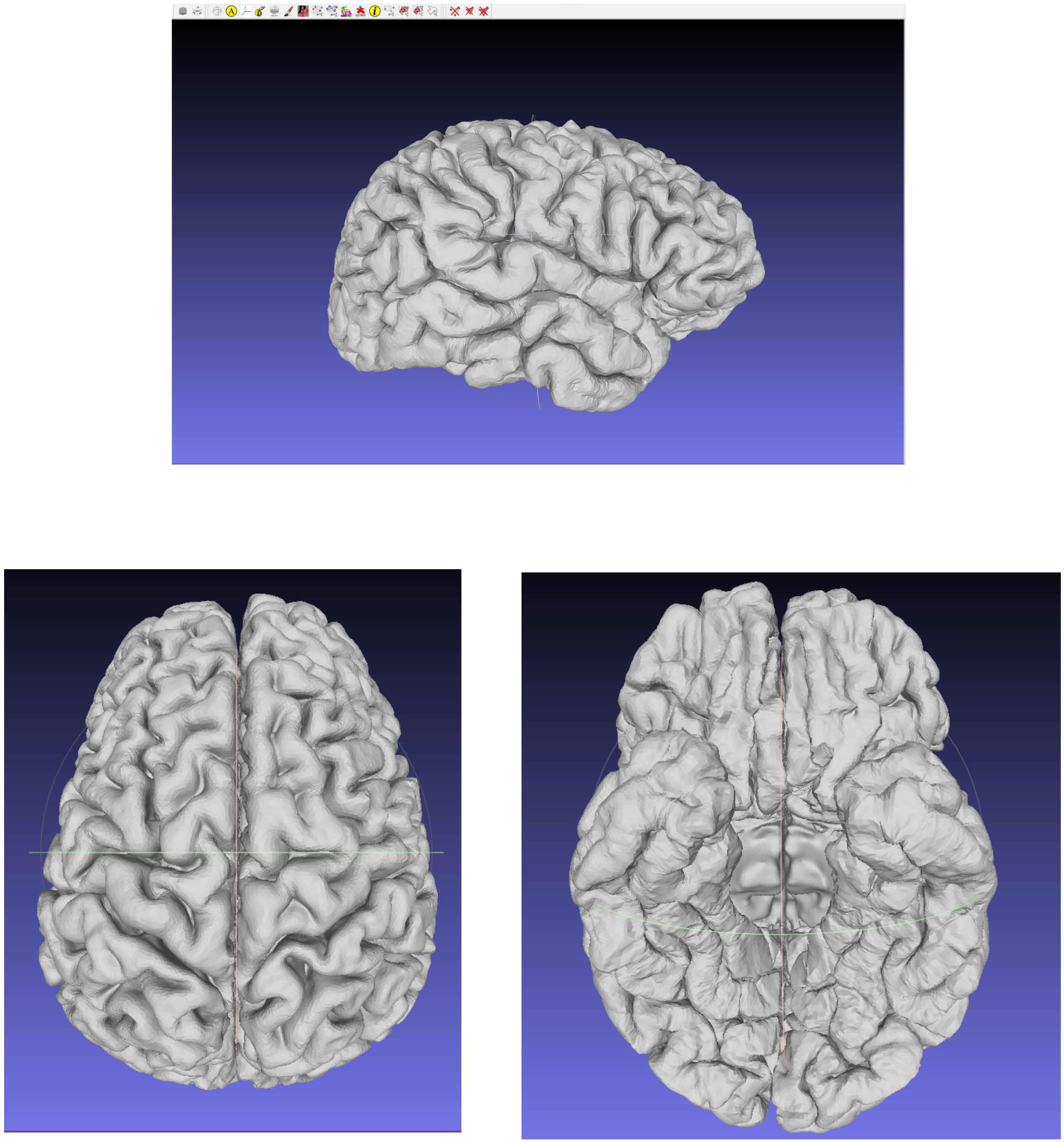


Figure 4: MeshLab Model

The smoothness of the model is clear from all three viewpoints, especially when the model is compared with the 'before' model in Figure 3. At this point the team has obtained a NIFTI formatted MRI image, segmented it by using the recon-all command in freesurfer, converted the .pial files into .stl files, and performed the quality control parameters on our newly constructed .stl file. The next step is to create more segmentations of different brain scans to validate our quality check process.

Quality Check Testing:

The team has been running numerous MRI scans through the pipeline to test for consistency in the quality checks. As previously mentioned, the pipeline creates a model that is smooth and consistently stays this way. Moving forward the team will continue to run MRI scans through this pipeline to check for consistency and accuracy.

Print Testing:

In the team's print testing process,two different materials have been tested. Those materials are resin and PLA (plastic). These are two materials that are fundamental to 3D printing. Resin is the more expensive material and tends to have higher print qualities in most cases than PLA. The team has compared the two models to determine which material would be better suited for the customer needs.

The Resin printer ultimately gave the most accurate results when compared to the PLA brain model. The resin material is very smooth. It is easy to see fine details within the model even when looking under the model. This material can be used to explain future surgical procedures to patients in great detail. This model was 25% of the original size of the brain. Currently, the team is in the process of printing another resin model that is 50% of the original size of the brain. The lab charged $15 for the use of materials. This would mean that for a full resin print of the brain, the team would be charged $30. At this point, the team is not concerned with the high price of the resin because a large quantity of resin was ordered. The team will be able to get our cost per print down. This will be our primary focus moving forward. Currently, resin is our number one material option.

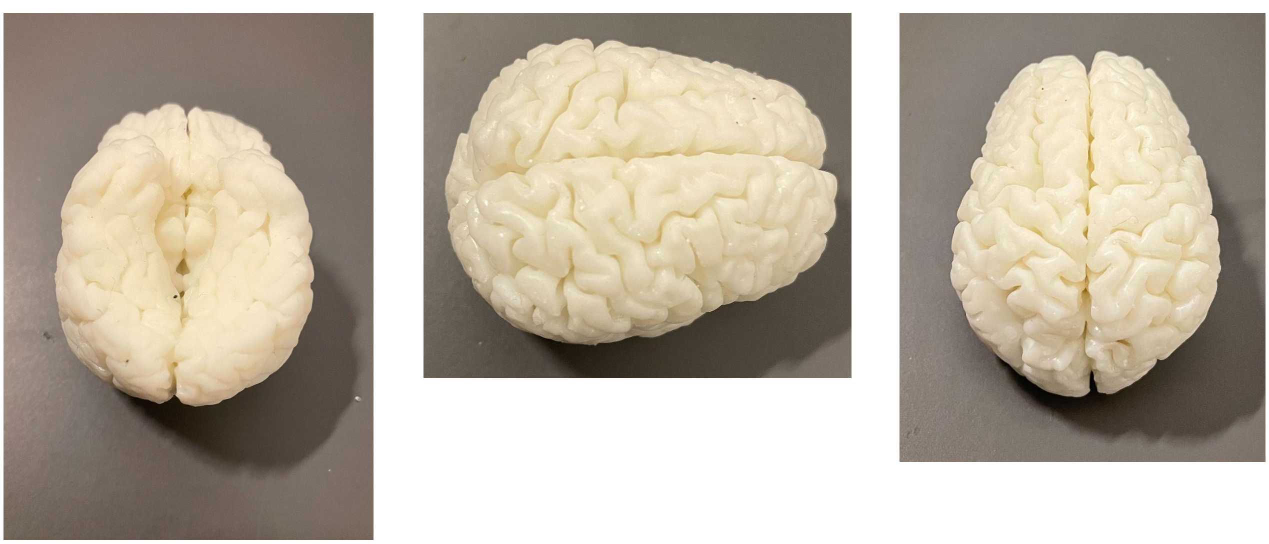


Figure 5: Resin Print Models

PLA material is the standard material used in 3D printing. It is best known for its low cost and lightweight properties. While the resin printer would cost $30 to print an adult sized brain model, the PLA would cost $20 for a model of the same size. This is a large difference in price, but when comparing the two models it is easy to see why the PLA is much cheaper. PLA printers use a layering technique where they increase the temperature of the plastic very high to melt it. Then, the plastic is dispensed one layer at a time by drawing out the necessary shape on the print bed. A fan is used to follow up the dispensing process to ensure that the plastic dries in the necessary shape. The problem with this method is that it leaves a lot of room for error. If the print bed isn't exactly level, then the model will come out imperfect. There were some noticeable errors with the team's PLA print that are not acceptable in the medical field. The details are not clear enough and the exterior is not smooth enough for our customers' needs. Because of this, the team will not be able to use PLA material moving forward.

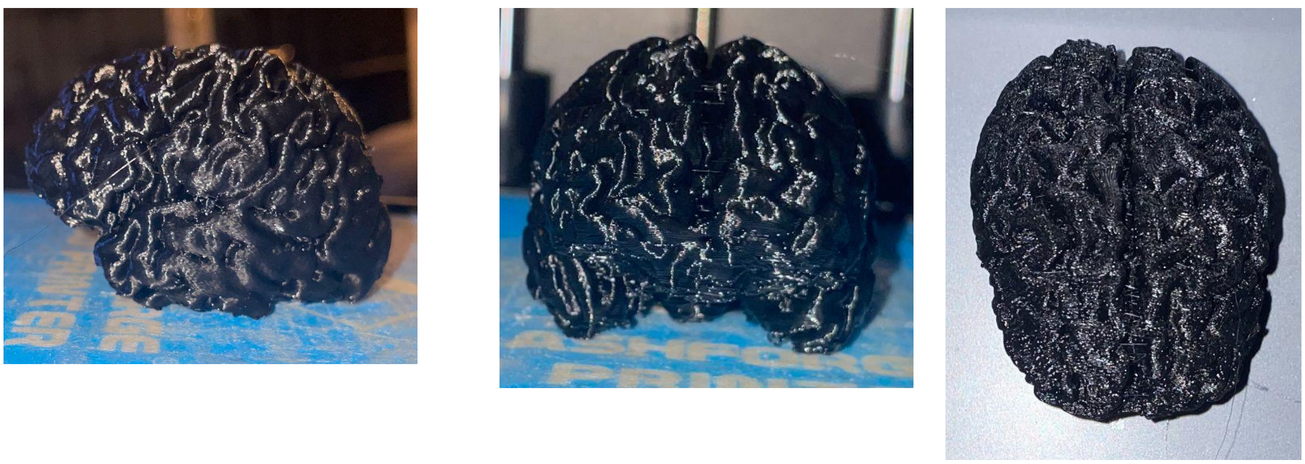


Figure 6: PLA Print Models

Beta Prototype

Pipeline

As previously stated, the pipeline for the beta prototype will be very similar to that of the alpha prototype. First, the MRI images will be uploaded into FreeSurfer, where it is segmented and converted into an STL file. From there, the brain model can be sent through MeshLab to be smoothed and a mesh is created on the outer surface. Finally, holes and inconsistencies are checked by sending the file through a couple of lines of code and the smoothing and retouching step can be repeated until the brain is of a sufficient standard and can be set to the 3D printer. The two additions to the beta prototype that were not featured, or only partially featured, in the alpha prototype are a finalization of the quality checking code and implementation of the inner surface of the brain, along with the use of multiple printing materials.

The beta prototype must contain functioning elements for all parts of the pipeline, and currently, the only quality check is in the form of sample code, which cannot be implemented in its raw form. For the beta prototype, the group will finalize the quality checking algorithms and implement them into the user interface in an easy to apply format. This will most likely take place using MATLAB since the group is familiar with the program and it is more than capable of handling fairly complex 3D models.

For the second addition to the pipeline, the group will strive to make the model slightly more accurate and detailed by adding a second surface to the model. There are two important surfaces when dealing with the brain: the outer surface and the gray matter-white matter interface. The alpha prototype currently only defines the outer surface and creates a homogeneous model below that face. For the beta prototype, the group hopes to display both the outer surface and the interface. This will be accomplished by first adjusting the method with which FreeSurfer is used to account for the second surface. After that, Meshlab can be used in the same capacity as with one surface, but changes must be made to the 3D printing process to make both layers visible. The plan to make this possible is to use two materials in the printing process. A transparent PLA filament will be used to print the outer layer and an opaque PLA will be used to generate the gray matter-white matter interface and as filler for the rest of the model. Implementation and testing of this addition will be carried out in Phase 5.

User Interface: Overview

In terms of a tangible beta prototype, two interfaces, one for the customer/user and one for the team, will be created and connected in order to create a means of customers being able to send in MRIs and receive 3D printed models in return. Having these interfaces will allow for the monetization of this pipeline process and will allow a system for customers to be able to have access to the pipeline (not entirely as the team will still have closed access to parts of the pipeline such as segmentation and printing). Both the customer and team interfaces will be connected via a server, so that files can be easily sent between the two.

User Interface: Customer View

The customer's interface will primarily be to upload the MRI scans that they wish to be printed out. The customer interface will be integrated into the project website, as one of the pages a user can access. This will allow the user to be able to read all about the project and inform them of what exactly will be happening with their MRI scan, and then proceed to use the program if desired. On the first page of the interface, there will be a welcoming introduction and a button for the user to get started, as shown in Figure 7 below.

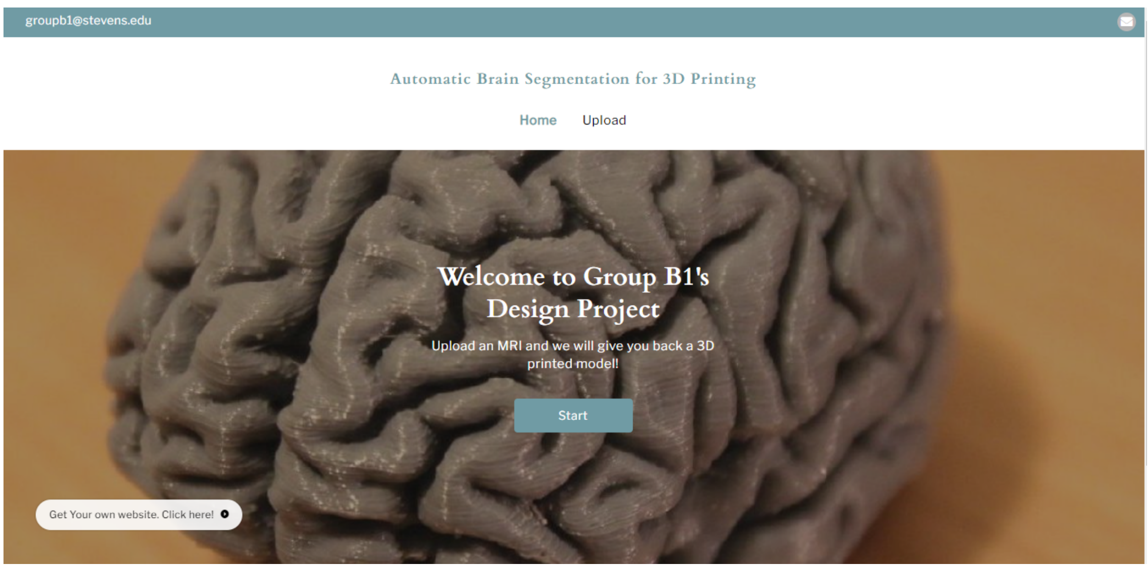


Figure 7: Example of starting screen for customer interface

The start button will then lead the customer to a second page, in which they will be prompted to upload their MRI scan, as shown in Figure 8 below. This MRI scan, which will be connected to a server, will then be sent to said server and be accessible for the team to then begin sending the scan through the project pipeline. Once the customer has successfully uploaded the MRI to the server, they will be sent to the next page, which will thank them for submitting the MRI scan and display the progress towards completion of their model, as shown in Figure 9 below. The user interface will aim to be relatively quick, easy to use, and aesthetically pleasing.

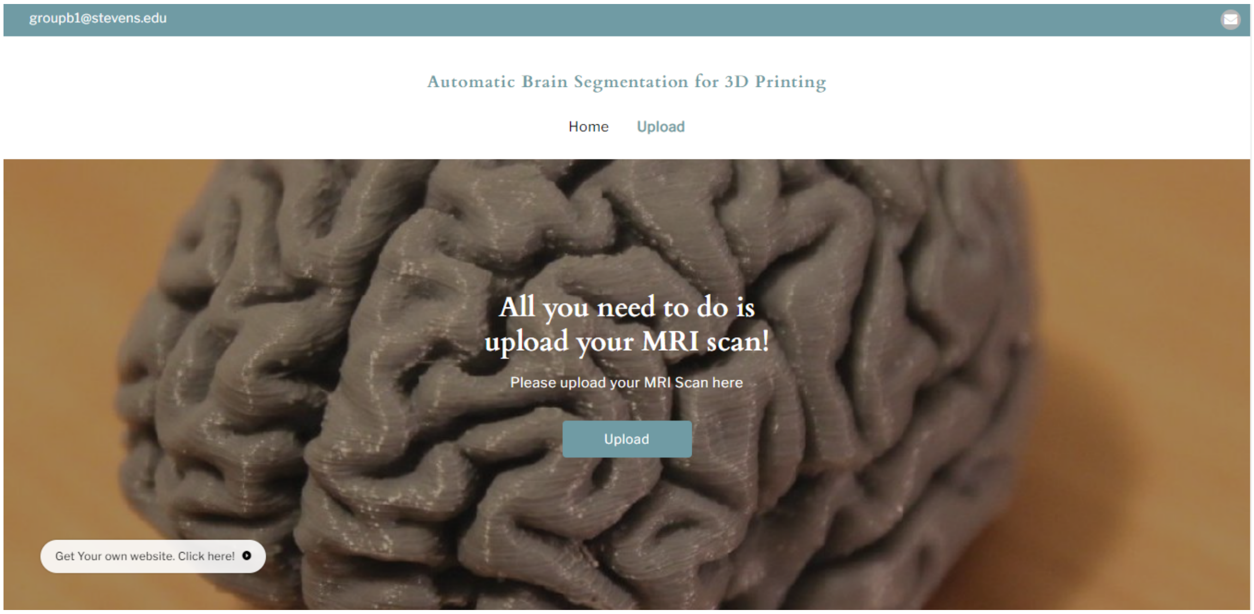


Figure 8: Example of upload screen for customer interface

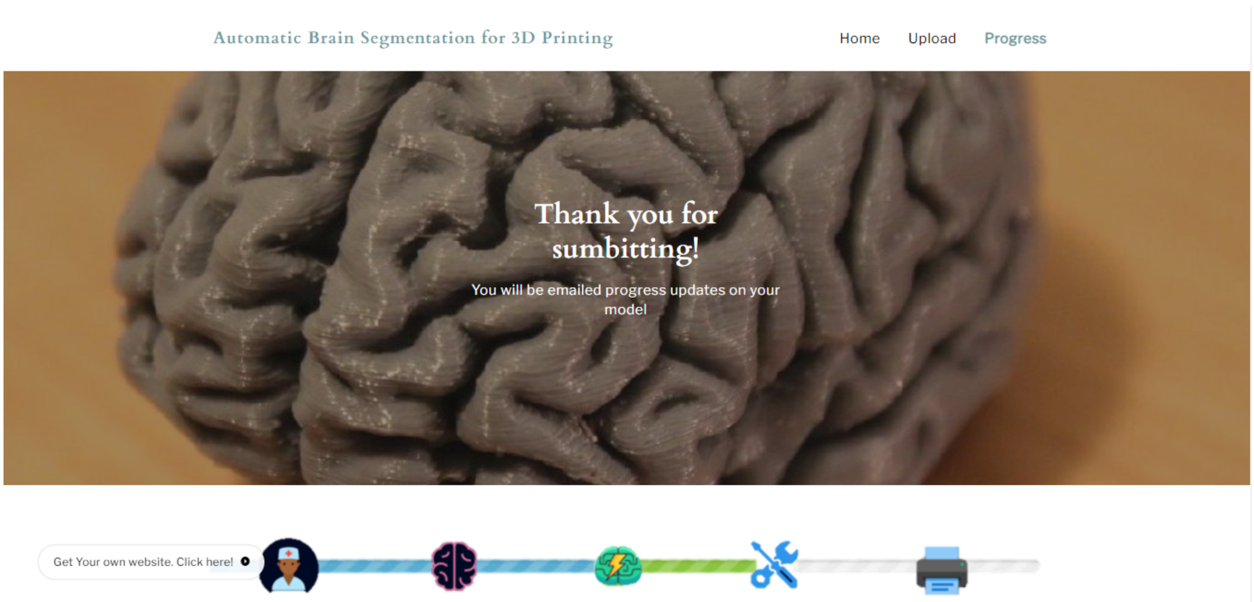


Figure 9: Example of final page for customer interface

User Interface: Employee View

As stated previously, once the customer submits the MRI and the scan is sent to the server, the rest of the pipeline will be performed using the employee's interface. This interface will be less explanatory and have many more functions. Mainly, the interface will have buttons that will send the MRI through each step of the pipeline. Firstly, the interface will have a button that allows the user to input an MRI scan to be run through FreeSurfer for segmentation. Next, there will be a button for uploading the newly created STL file to MeshLab to be smoothed. There will then be a button for the STL to then be inputted into MATLAB to run the final repairs and quality checks. Lastly, there will be a button to slice the STL file for it to finally be ready to 3D print. As shown in Figure 10 below, the employee interface is straightforward and would be easy to teach to any new employee who would need to use this interface. To make usage even easier, the interface will have references for FreeSurfer, Meshlab, and 3D printing, in order to answer any extraneous questions the employee may have. The employee interface will be designed to be easy to navigate, straightforward, and informative.

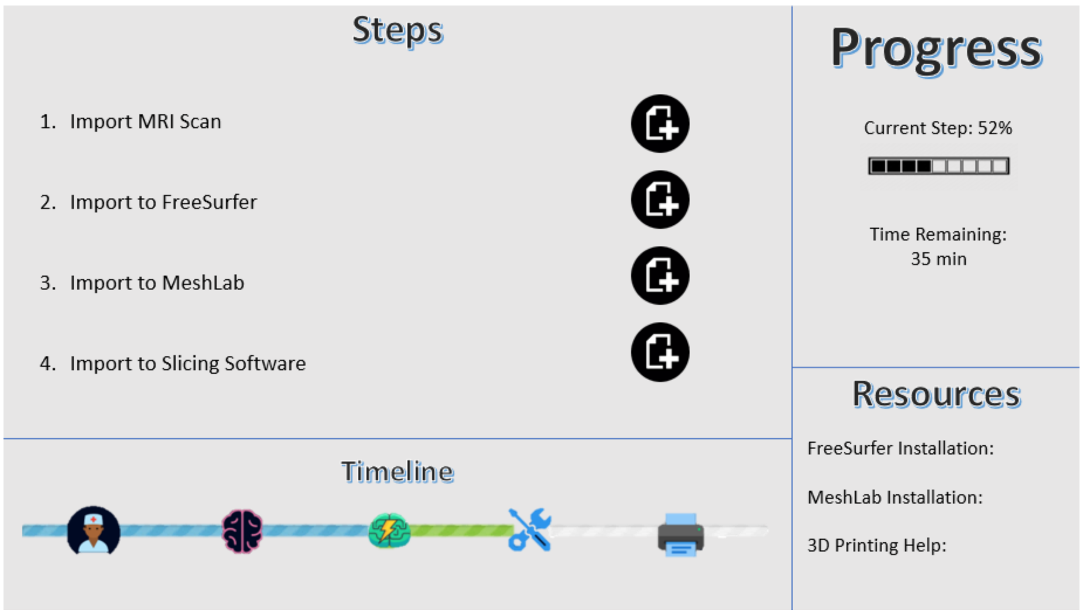


Figure 10: Example of Employee Interface

Server

The team is looking into viable servers to use as a means of collecting, storing, and using MRI scans that customers send in. There are many relatively cheap servers with a reasonable amount of storage, but the main server provider the team is looking at is the Amazon Web Services. The AWS has high storage and computing power for reasonable prices. In fact, AWS offers a free 12-month trial that includes 5 GB of storage and 750 hours of compute capacity. This free trial is more than enough for the team to test and analyze their interfaces through numerous iterations.

Cost and Manufacturing Issues

In terms of issues with costs, there are not any potential issues. The only costs for this pipeline would be printing filament (if needed) and potential costs for the server. All other license costs for software and coding IDEs are covered by the student accounts. In terms of manufacturing issues, there are potential issues in print and segmentation time. Running numerous scans through the project pipeline is very time consuming and requires a lot of waiting. Subsequently, the 3D printing of models can take a while too, with potential printing issues occurring, such as the nozzle clogging or imperfections with the bed adjustments.

Timeline for Build and Performance Testing

Firstly, the customer user interface needs to be created. As previously mentioned, the team plans on implementing the customer interface into the project website, which is currently on Wix. This step is relatively light coding-wise. The team plans on finalizing the customer interface within the first 2 weeks of the next phase. Next comes the server, which the team plans on setting up about a week after the customer interface is set up. Lastly comes the employee interface, which is the most coding intensive portion of the build, as a new interface needs to be made from scratch and contains many more functions than the customer interface. The team plans on taking 3 to 4 weeks to complete and finalize the employee interface. In terms of performance testing, the testing is similar to that of the alpha prototype. The team will run multiple MRI scans through the pipeline, now with interfaces present) to test each function of both interfaces to make sure that they all work and meet quality standards.

Gantt Chart Timeline

Below is the timeline for the team's progress in Phase 4, as well as planned progress for Phase 5. The full Gantt Chart can be found in A1 of the appendix.

	Task	Assignee		Start	End	Progress
	Phase 4:		-	18/Jan	17/Feb	0%
1	Smoothening and Quality C...	Unassigned	-	18/Jan	08/Feb	0%
2	3D Printed Model Testing	Unassigned	-	18/Jan	08/Feb	0%
3	Beta Prototype Fabrication ...	Unassigned	-	08/Feb	15/Feb	0%
4	Phase 4 Report	Unassigned	-	15/Feb	15/Feb	0%
5	Phase 4 Presentation	Unassigned	-	17/Feb	17/Feb	0%
	+ Add task + Add section					
	Beta Prototype Fabrication:		-	17/Feb	31/Mar	0%
8	Customer Interface Creation	Unassigned	-	17/Feb	24/Feb	0%
9	Server Setup	Unassigned	-	24/Feb	03/Mar	0%
10	Employee Interface Creation	Unassigned	-	03/Mar	31/Mar	0%
	+ Add task + Add section					

Figure 11 : Timeline of Phase 4 and Fabrication Plan

Budget

In terms of cost for the project, the bill of materials has not changed much from the previous page except for the addition of a storage server and the cost resin filament. This total still fits well within the team's allotted budget.

Table 1: Current Bill of Materials

BOM Item Number	**Description**	**Vendor**	**Cost (each)**	**Quantity**	**Purchased**	**Received**
1	Black PLA Filament (1 kg)	Micro Center	$15	2	Yes	Yes
2	Natural PLA Filament (1kg)	Micro Center	$19	2	Yes	Yes
3	UV-Curing Resin	Any Cubic	$30	1	Yes	No
4	AWS Storage	AWS	$0.50	1	No	No

dAppendix

A1: Full Gantt Chart