Automatic Brain Segmentation for 3D Printing

Phase 4 Report

Due: April 28, 2022

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

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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 6, which includes the project statement, a detailed summary of all of the progress made in the past phases, final product design, and any lessons learned about the design process. This phase was all about refining the beta prototype, making sure that all of the key components in making this project operational were in place, and finalizing a business plan and pitch for this proposed product. The following report will outline how this group achieved all of the progress that they have made and the lessons they learned along the way.

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Project Statement

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.

Detailed Summary

Phase 1

This project began with a question: is it possible to 3D print a patient's brain? Naturally, that is where the group had to start their development. Phase 1 was mainly about determining if it was feasible to 3D print a patient's brain and, if so, how it could be achieved. This led to the group doing a state-of-the-art review to find any current groups that were doing this or something similar. As it turns out, there are a few free-lance workers that are modeling patient's brains at the moment, but they are all done manually and are very costly. This not only verified the possibility of creating a product like this, but also identified a hole in the current market. This team could outperform the current producers and create a more widely available product if they were to streamline the creation of the patient's brains and make the entire process automatic. This would allow them to take on more customers and output products more quickly and at a lower cost.

Next, the group had to evaluate the needs and specifications of both the customers and the stakeholders of this proposed project. In order to do so, they created a chart that would list the needs generated by the team and through various interviews with the target demographic (Table 1). This provides an easy way to view all of the requirements for this project and their relative importance.

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

Table 1: Customer Needs Chart

The final portion of phase 1 was to create a very rough plan as to how the models would be made and possible areas that could be automated. Through research and discussion with their advisor, the group compiled a set of steps that would be able to take them from a patient's MRI scans to a 3D printed brain. First, the MRI file must be obtained. These files come in an array of different formats, but the one of choice is as a NIFTI file. Next, the brain can be sent through a segmentation software that would separate the actual brain matter from the extraneous parts of the head such as the skull and eyes. After that, the file can be put into a meshing software in order to smooth the surface of the brain and fix any holes or abnormalities that may have arisen during the segmentation, and finally, the file can be converted into an STL file and 3D printed. This led the group to creating their first iteration of the pipeline that the brain scans would follow to become 3D printed.

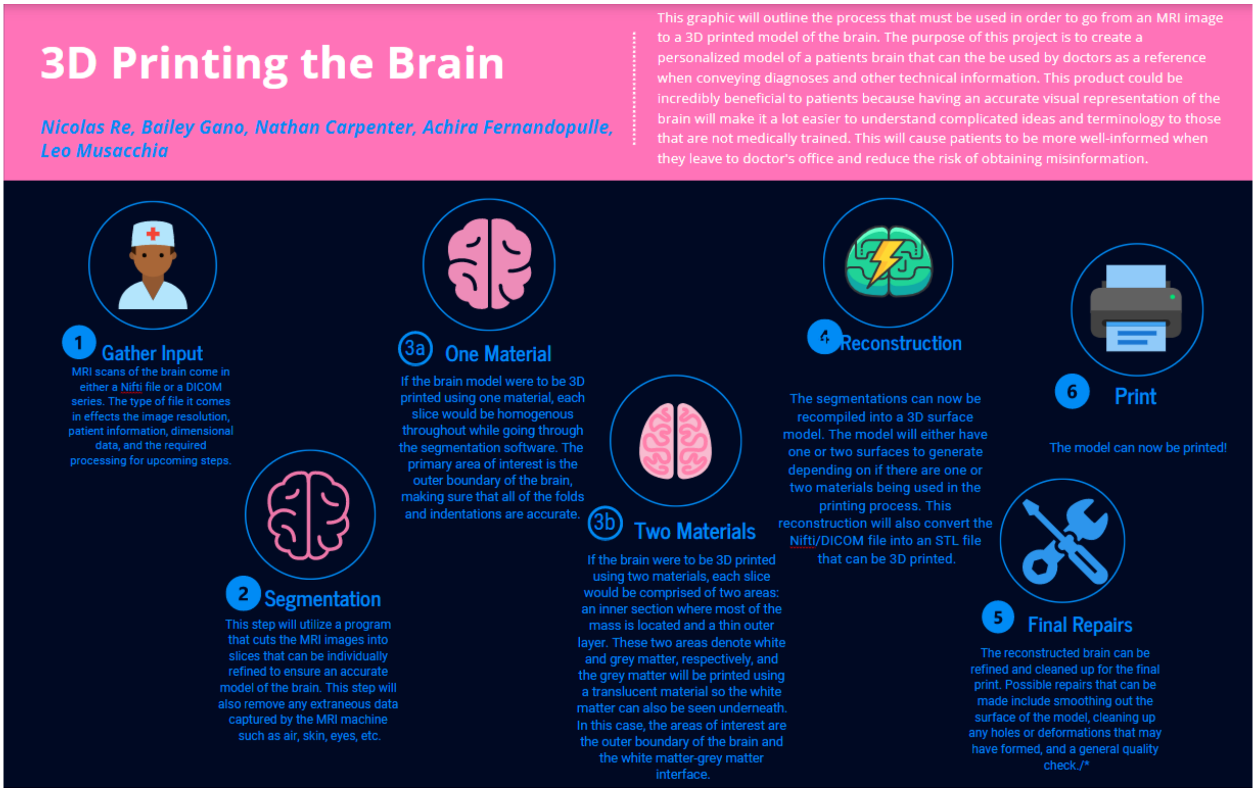


Figure 1: First Iteration of Project Pipeline

The print was mainly focused on two portions of the brain: the outer surface and the white matter-gray matter interface. As pictured below, the human brain is composed mostly of white matter, with a small layer on the outside made of gray matter. The group wanted to represent these layers by using two different colored 3D materials. The gray matter would use a translucent material so the customer could see inside to the surface of the white matter. For the scope of this project, the group decided that the inside of the brain was not necessary to print accurately since the product focuses on the surface of the brain.

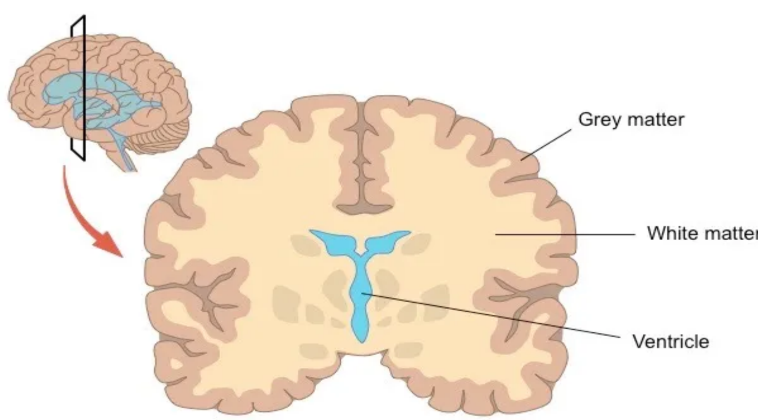


Figure 2: Brain Matter Diagram

Phase 2

Phase 2 was all about creating a technical analysis for this project. This included an analysis and comparison of the available software for the rough outline that had been created in Phase 1, and an analysis of the physical model itself. It became evident that there were three main areas where outsourcing a software would be incredibly beneficial: the segmentation, the meshing/smoothing, and the quality assurance. The segmentation software was the first to be addressed since it is the most important part of the process. MRI scans come in the form of a NIFTI file which is basically a stack of 2D images that make up the brain. A segmentation software will compile that stack into one 3D image, so it was vital that the group chose an effective software to use. After extensive research, the team ended with three softwares of interest: ITK Snap, 3D Slicer, and FreeSurfer. These softwares were then put into a simple chart (Table 2) that could analyze their relative scores based on certain criteria and FreeSurfer was chosen. Similar steps were then followed to find the smoothing software, Meshlab, and the quality assurance software, Mexhmixer.

	Segmentation Software		
Criteria	ITK-Snap	3D Slicer	Free Surfer
Automization	1	2	3
Usability	1	2	3
Segmentation Time	1	1	2

Table 2: Segmentation Software Comparison Chart

The second portion of this phase had to do with performing a technical analysis of the brains themselves. There are many different factors that go into making the final print as accurate as possible, so it was vital to dissect each one of them to ensure they aligned with the group's needs moving forward. First, the group wanted to get a better understanding of what exactly the MRI would be outputting and how the file could get converted into a 3D image. This will help later down the line if there are any bugs that need to be fixed with the code or if the brains are not coming out in the condition that the group deems acceptable. An MRI is made up of a set of 2 dimensional pictures taken at different layers of the brain. These images have a thickness, about 2 mm, and can be stacked on top of each other to form a full brain. The segmentation software goes through each image individually, removes all of the unwanted parts, and stacks the images. This outputs a rough 3D model of the brain that must then be smoothed and checked before it can be printed. With this information, the group had a better understanding of how the scan and segmentation software functioned and what exactly needed to be done for the smoothing portion.

Next was an analysis of possible materials that would be used to print the brain. The material chosen had to be compatible with the 3D printers available, it had to be durable enough to withstand shipping and handling, and it had to be cost effective. The two materials chosen by the group were PLA and Resin. PLA (Poly Lactic Acid) was chosen for its durability as well as its light weight and low cost. It is a very common 3D printer filament that has good structural integrity and a long shelf life. Resin, on the other hand, is slightly more expensive, but it is just as durable and slightly malleable so it mimics the brain matter better than the PLA. It also produces a very smooth and glossy finish. These materials will be thoroughly tested in later phases.

Phase 3

Phase 3 led the group to creating an alpha prototype. This began by creating a simpler and more direct pipeline as pictured below. It contains all of the same components as before but in a more concise fashion which makes it more easily presentable.

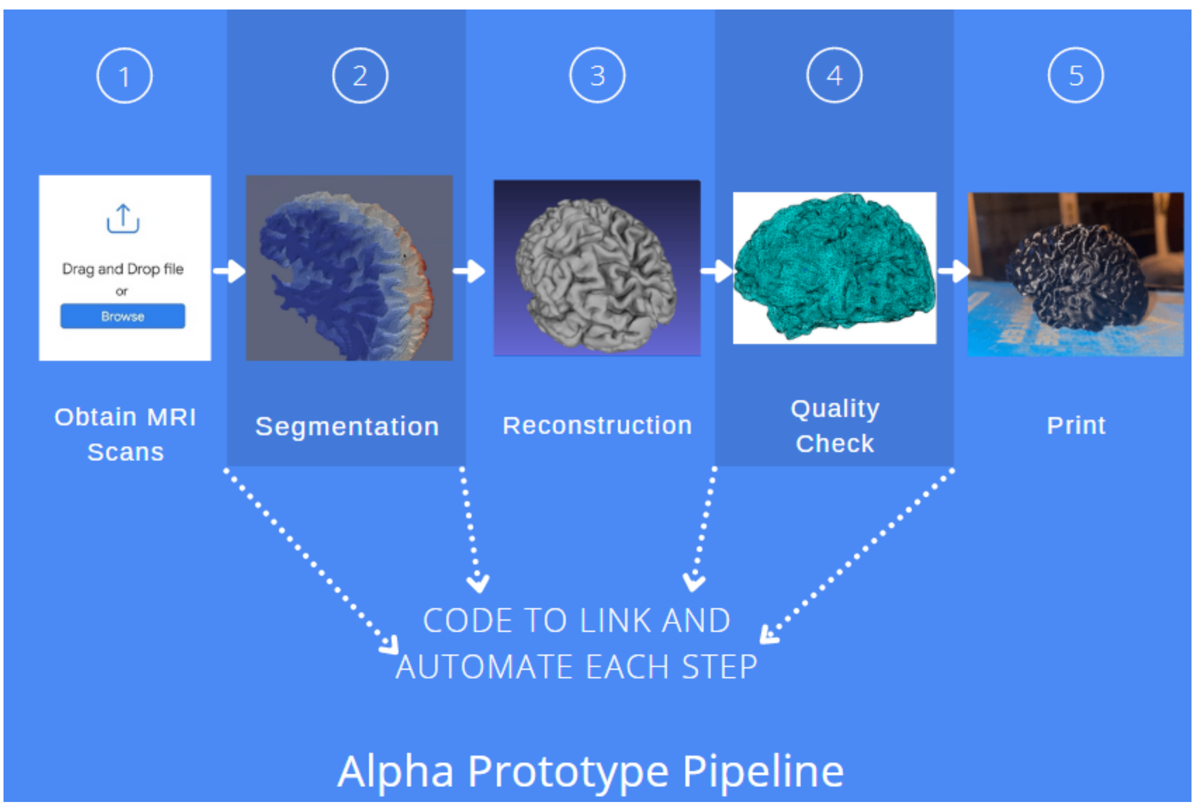


Figure 3: Alpha Prototype Pipeline

The pipeline shows the five major steps that each brain will go through to obtain a model: obtain the MRI scans, use the segmentation software, FreeSurfer, to compile the scan into a 3D model, use a smoothing software to make sure the brain is at a presentable quality, perform a quality assurance check, and finally, print the brain. The quality assurance check was planned to be created using MATLAB, due to its compatibility and built-in MRI packages. The pipeline also shows that the group intends to link all of the softwares with code so that it is fully automatic.

In this phase, the team was able to follow all of the steps for the first time and print their first brain. The MRI scan was provided by their advisor and the first test run commenced. This run was done manually to make sure that all of the steps in the pipeline were funational before trying to make it automatic, which will be done for the beta prototype. First, the MRI scan was run through FreeSurfer in order to do all of the segmentation. This is a complex program that has been utilized since the beginning of this project, so that portion ran very smoothly. Next, the output from FreeSurfer was sent to Meshlab to perform smoothing operations. The program contains many different types of smoothing, but the group decided to follow a specific protocol for the best results. The first step was to use the “Flaaten All Visible Layers” function in order to fix any of the layers that may have been segmented incorrectly. Next, the “Quadric Edge Collapse Decimation” function was used to remove any holes or inconsistencies that may have occurred during the segmentation process. Finally, the “HC Laplacian Smoothing” operation was performed in order to smooth out the rest of the model. Lastly, a manual quality check was made of the model because the program was not yet ready for use by the group and the first brain was printed using a gray PLA filament.

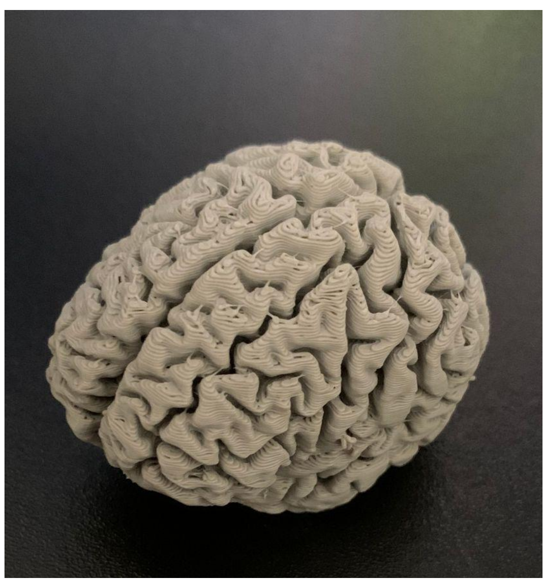


Figure 4: First Brain Print

As seen from the image above, the final product outputted a full brain, however, there was much room for improvement. This brain was not very smooth, there were some holes created by the filament, and this model was only 1:4 scale of the actual size of a brain. All of these problems were addressed in the following phases of this project.

Phase 4

Phase 4 focused on further testng of the alpha prototype, as well as creating a plan for the beta prototype. As the testing of the alpha prototype continued, many more prints were made with varying sizes and materials in order to determine the parameters that the group would stick with. In the end, they found that the bigger the brain, the cleaner the print, so printing a brain model 1:1 would be ideal. Also, the group was able to directly compare PLA with Resin. Two brains were printed at the same scale (Figure 5) and it was determined that the group would continue with the Resin material. Though it is slightly more expensive than the PLA (about $10 per print) the quality of the brain was better enough to justify the cost.

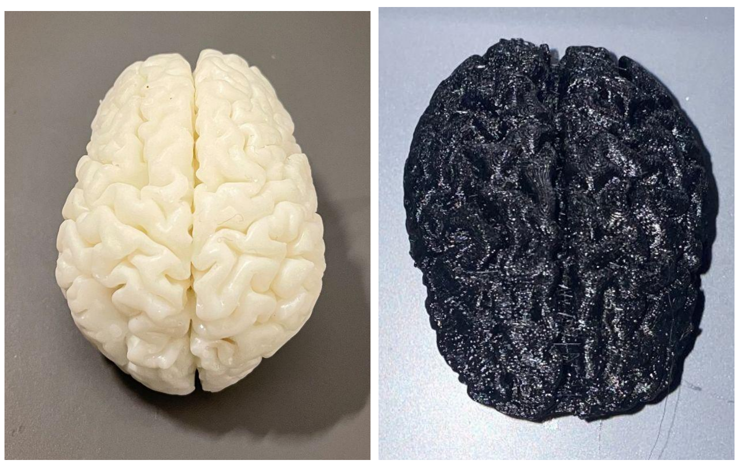


Figure 5: Side-by-Side Comparison of Resin Brain (left) and PLA Brain (right)

Overall, the alpha prototype displayed two key areas for improvement: the printing quality and the quality check program. The alpha prototype showed that the quality check code created in MATLAB was time-consuming, not very efficient, and the smoothing results had room for improvements. This led the team to create the beta prototype with these in mind. The beta prototype was planned to implement a new quality check code and create more accuracy with the second surface of the model. Most importantly, the team decided that the beta prototype will consist of a customer interface and an employee interface. 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 6 below. 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.

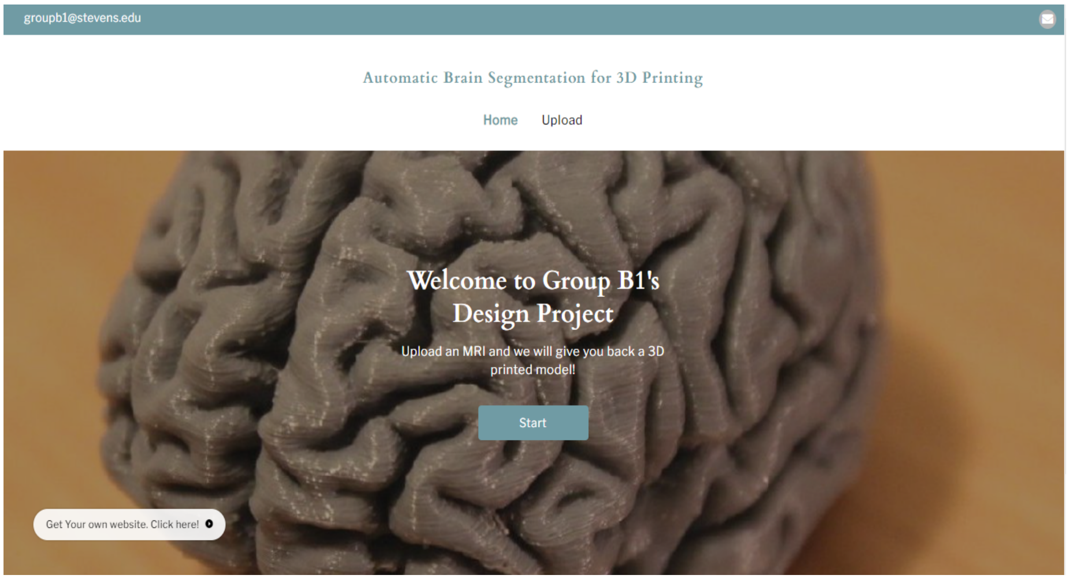


Figure 6: Example of Introduction Page of Customer Interface

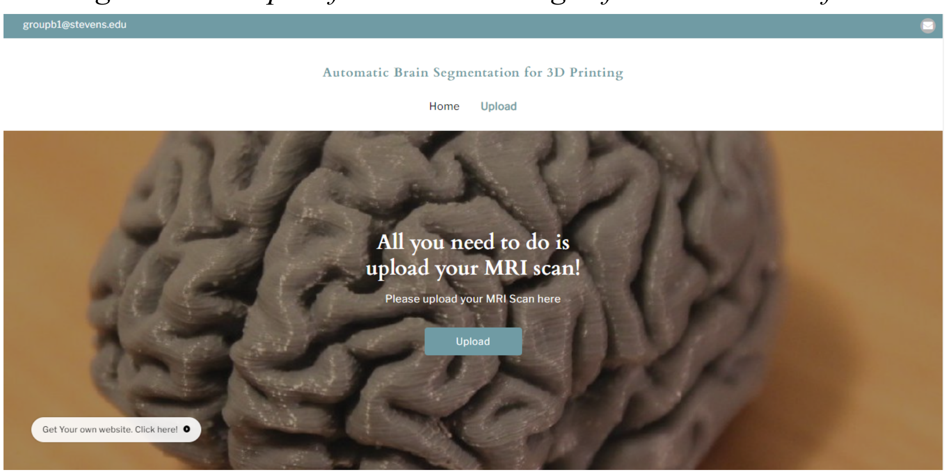


Figure 7: Example of Second Customer Interface Page for Uploading MRI

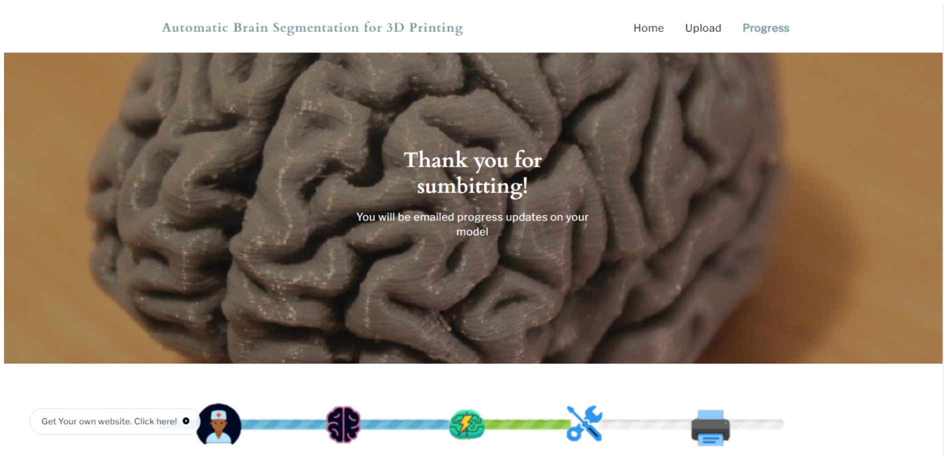


Figure 8: Example of Thank You Page of Customer Interface

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 9 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.

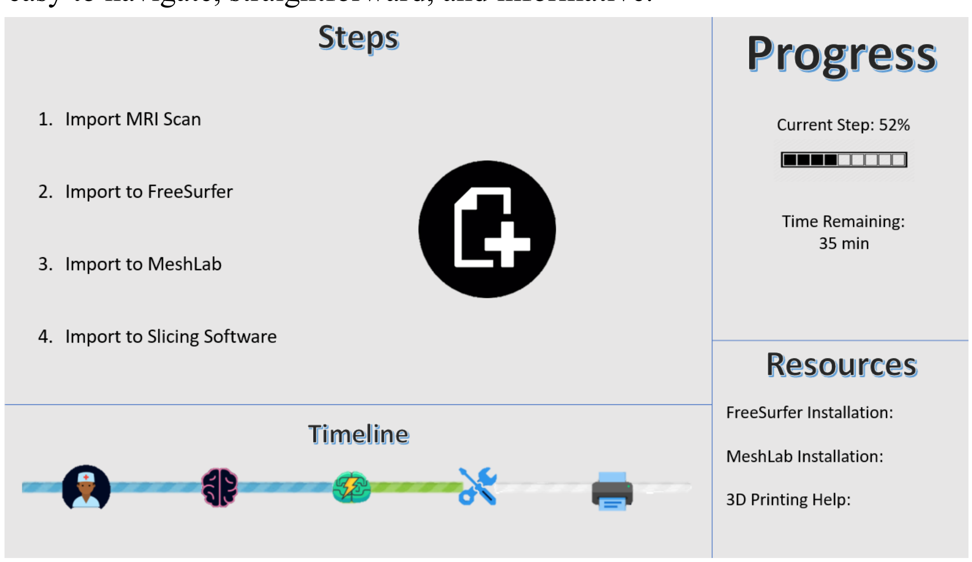


Figure 9: Example of Employee Interface Design

The team also planned to implement a server that stores the user inputted MRI scans, so that the employee interface can access these submissions and run them through the pipeline. With this combination of interfaces and server, the fabrication plan is formed as shown in the figure below.

Figure 10: Beta Prototype Outline

Phase 5

In Phase 5, the beta prototype was created and tested, and the final design was detailed. After Phase 4, the team deliberated that the server and separation was unnecessary for the scope of the project, and that one conjoined interface that showcases the whole pipeline would be more fitting and efficient. Additionally, rather than have to manually input the file into each part of the pipeline, the team decided that the UI should have just one input button. This decision was made for the sake of the Innovation Expo and project, but in the future the two separate Additionally, the team decided that the final quality check would be done through Meshmixer, as it is less time consuming, produces similar if not better results, and can be automated using the Meshmixer API. With these decisions made, the group proceeded to create the UI and automation process.

As decided before, the UI was portrayed as a website using HTML. The purpose of this website is to allow customers to directly upload their MRI scans and view the progress that is being made during the process of 3D printing it. The UI also contains a portion for the employees of this proposed company that walks through the steps of 3D printing the brain and allows for the alteration of the brain at any point in the pipeline. All of the screens that will be viewed by a customer are located in the Appendix. The UI contains a submission section, the purchasing section that allows for the user to choose from a variety of sizes and colors, and a subscription plan option for Finally, during these phases the group created code to automate all those who want to bulk purchase models (such as hospitals and clinics). Finally, during this phase the group created code to automate all of the steps of the pipeline. The language that is used for this is Python since all of the programs used are compatible with it. These codes can also be viewed in the Appendix. The last portion of this project would be to combine all of this code into one coherent script that can be run with one push of a button. The group, however, is currently incapable of fulfilling this task because it would require a single server to be run on which, if this project were to continue, would be used at the central location that the company would run out of.

The FreeSurfer code, shown in the Appendix, takes MRI scans, segments each slice to separate the white and gray matter, reconstructs the pieces into a 3D model, and converts the model into a .stl file. As shown in the figure below, the input is an MRI scan and the output is a .3D brain model.

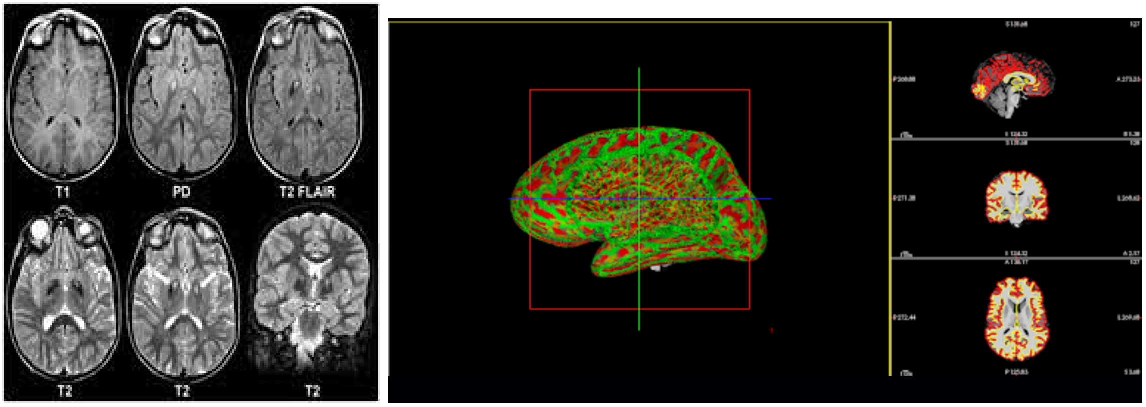


Figure 11: Input (top) and Output (bottom) of the Freesurfer segmentation step

The Meshlab code, shown in the Appendix, takes the outputted .stl file of the FreeSurfer stage and smoothens the model to improve the model quality and accuracy, as the FreeSurfer output has many inaccuracies and discrepancies. The unsmoothed stl file is inputted and a smoothened stl file is outputted with this code, as shown in the figure below. The new model is clearly more smooth and accurate than the input model.

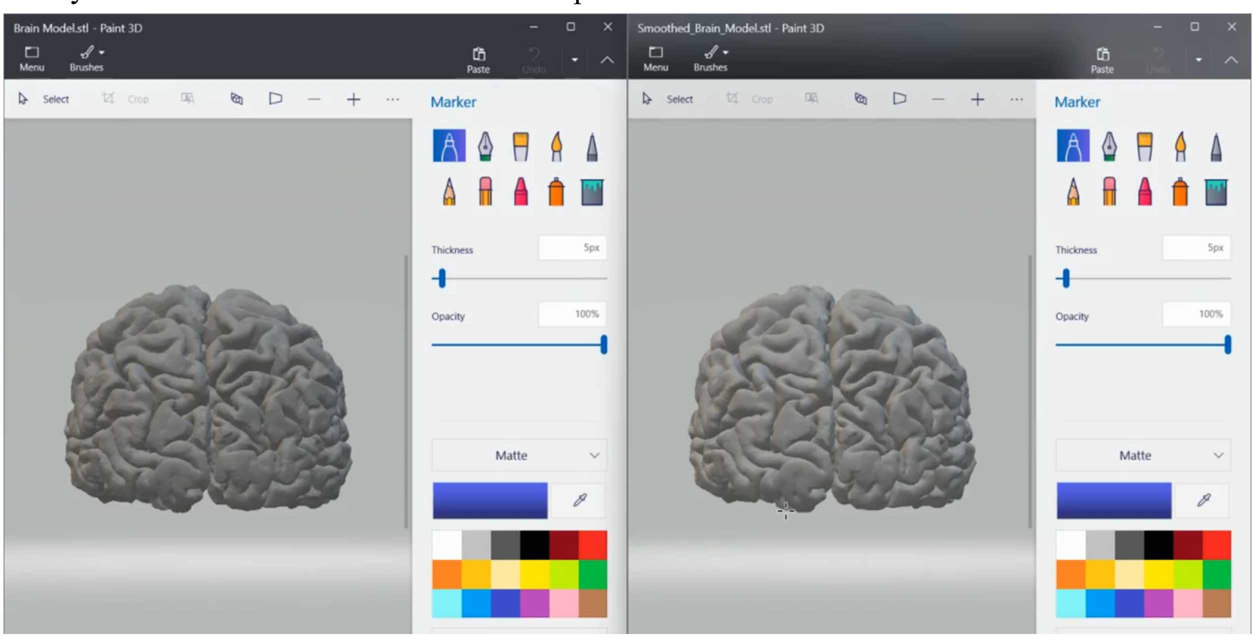


Figure 12: Input model (left) versus output model (right) of the Meshlab stage

The Meshmixer code was done in VisualStudios in conjunction with the Meshmixer API found on GitHub. This API allowed the team to remotely control Meshmixer and create a code that automatically performs the final quality check smoothing, as shown in the code found in the Appendix. The code runs the remesh function and increases the mesh density to make the model more smooth and accurate when printed. The input is the stl file from the Meshlab output and the output is the finalized brain model that is ready to be 3D printed, as shown in the figure below.

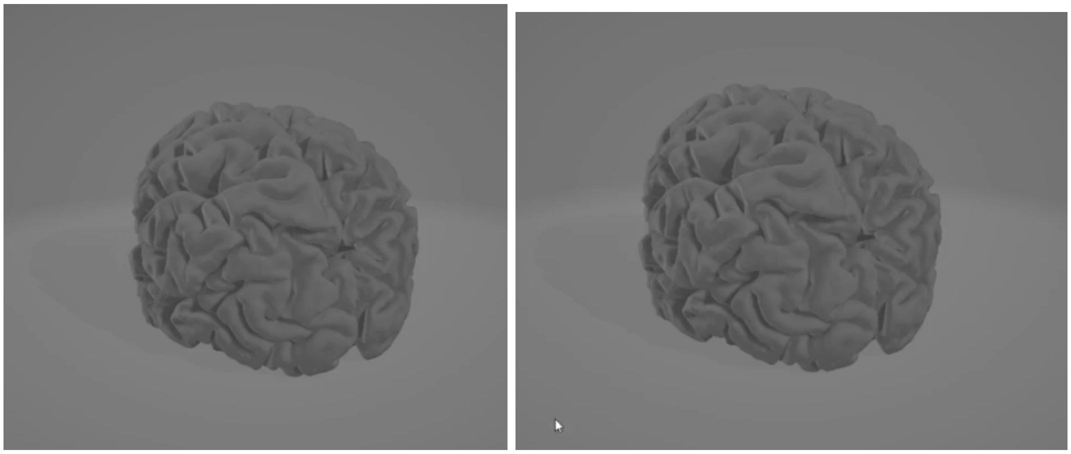


Figure 13: Input (left) versus Output (right) of the Meshmixer stage

Regarding the Meshmixer portion of the pipeline process, the team also worked on improving the model quality, and thus tested creating lattice structures in Meshmixer. Utilizing lattice structures have a good strength-to-width ratio, and make the models more lightweight and cheaper to print. Creating lattice structures (shown in Figure 11 below) in Meshlab is done using the Make Solid tool, Make Pattern tool. The team found that Composition Mode and Clip to Surface are important parameters that ensure that the infill supports the exterior surface.

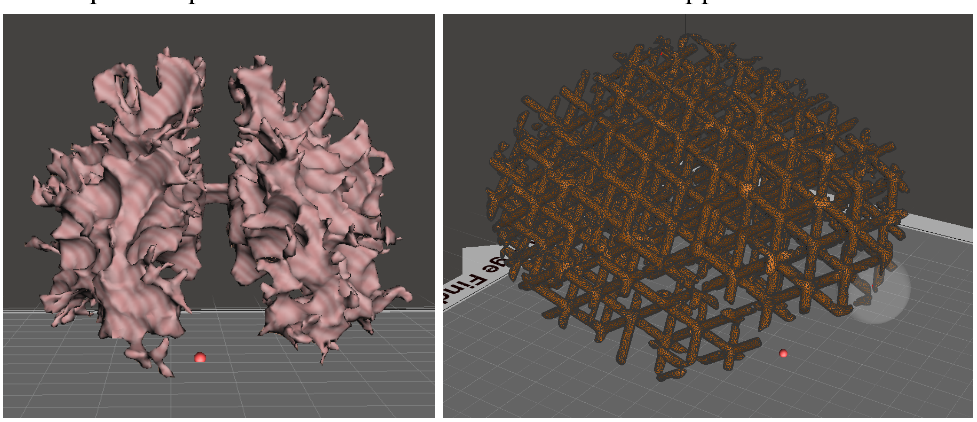


Figure 14: Lattice Infill Structure made in Meshmixer

As the team continued testing the beta prototype and printing more models, the team also decided to print out brain models from different stages of the pipeline to compare the model quality and validate the process they created. Both of the models shown in the figure below were printed using resin. The model on the left (pink) was created after the FreeSurfer portion of the pipeline while the model on the right (white) was printed after the final Meshmixer smoothing. As clearly shown, the finalized model after all the smoothing processes is much more smooth, accurate, and high-quality of a model than the model created right after segmenting and reconstructing in FreeSurfer. This validated the team's pipeline process and showed that the model greatly is improved using the process.

Figure 15: Comparison of model before smoothing (left) and model after smoothing (right)

Phase 6

For the ongoing Phase 6, the team has continued to update their command scripts to automate the Freesurfer and Meshmixer, update the UI, and print brain models to test the project pipeline. Regarding the printing of models, the team attempted to print a multi material model using the Objet 350 Connex 3 printer. The model would separate the white and gray matter of the brain model. However, the Stevens Proof Lab notified the team that the printer was broken. Instead the team decided to work on printing a PLA model with clear material for the gray matter and red material for the white matter. This model is currently being printed as of the creation of this report.

Key Insights and Lessons Learned

This project contained many learning opportunities for the team. Given that this project was heavy on coding, and the members of the team had very minimal exposure to code, many hours were spent in order to gain as much knowledge as possible to have some background on the skill. This was a great lesson as in the end the group was able to create an automatic process by coding through different softwares and ultimately to a printer. It showed that even though the task seemed insurmountable at the start the team was able to overcome this handicap in skills. Another big lesson learned was the fact that not all the plans and expectations that were set at the beginning of the project are going to be met or followed exactly. There are going to be obstacles and detours along the way and in the end not everything that was hoped for is going to be accomplished. Also plans are going to have to change based on what is presented. For example the original plan was to use Matlab as the software to both connect the other softwares together and build the user interface. In the end that proved to be very difficult and python was utilized. There were several other instances in which the original plan did not prove viable.

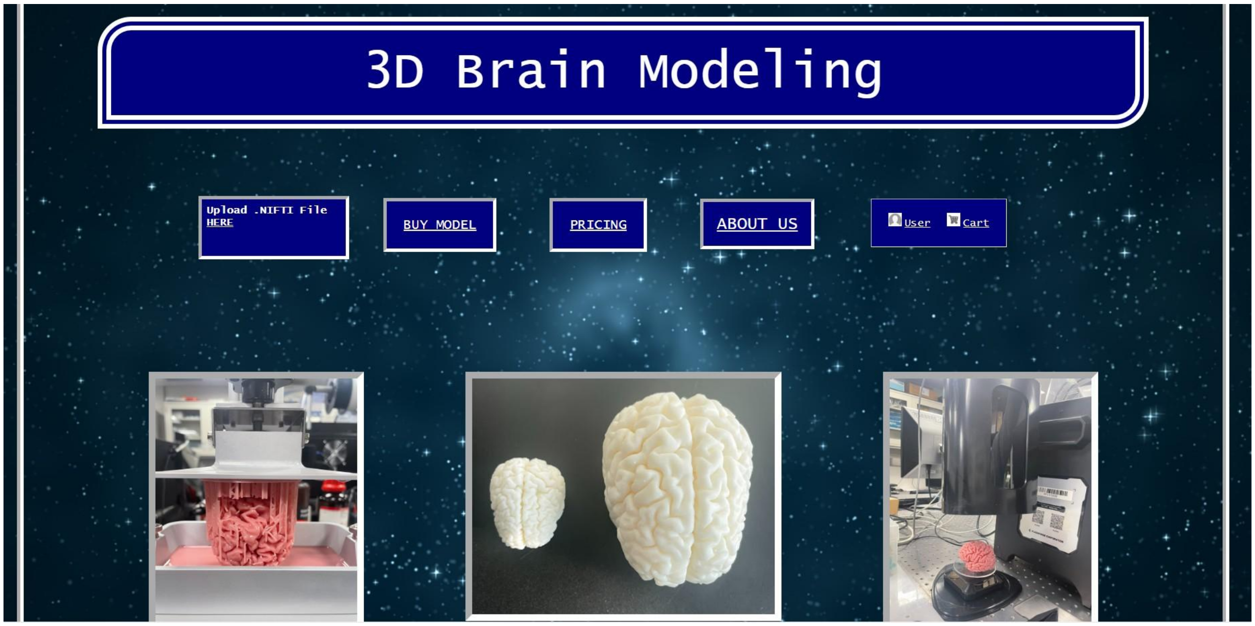
Building off of that lesson another idea is to do more research earlier on in order to create a more detailed and well thought out plan in order to limit the amount of roadblocks that will be faced. By having a more concrete setup for the project it allows for the project to run more smoothly along with being more certain in what is being done. This is something that the team should've done more of instead of just diving into software. This would have reduced the amount of time that was wasted on some aspects that ended up being scratched or changed completely.

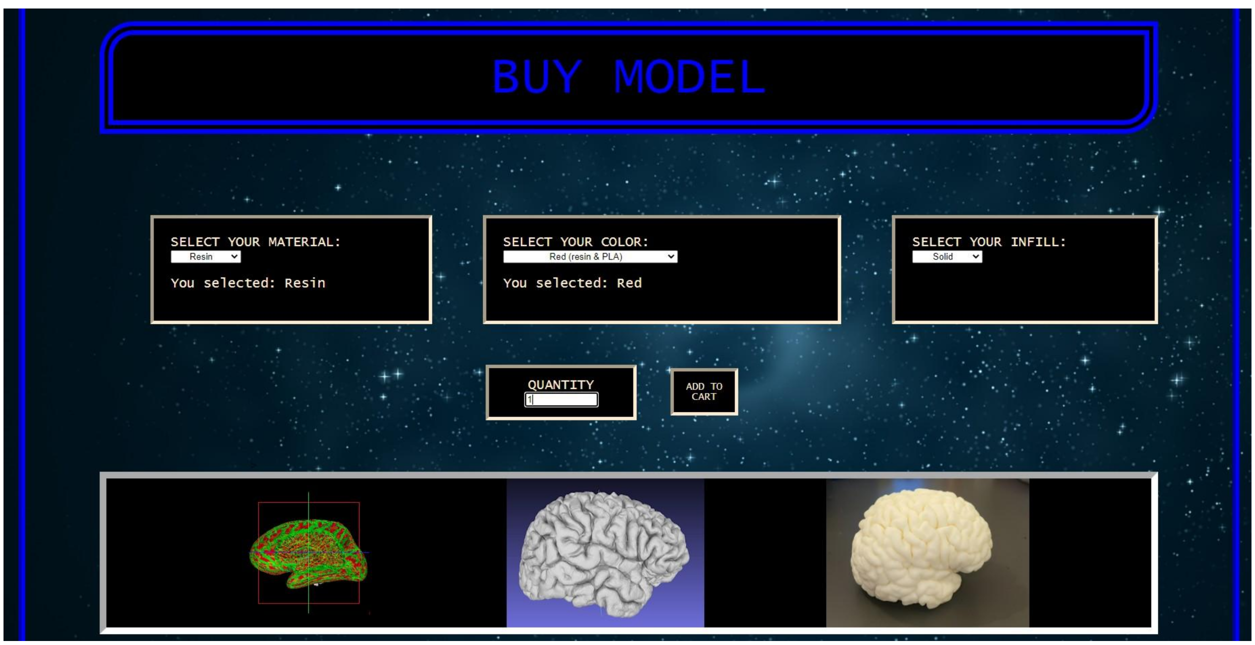
Looking more specifically at the process, testing is one of the most important aspects for a project to be successful. For our project we started off just focusing on the coding and only viewing the digital 3D model that was created within the software. By looking at this version of the model it seemed very smooth and accurate. However, later on when the team started to print the models it was evident this was not the case and further smoothing and enhancing was needed. Therefore another step for quality checking was added using Meshmixer. From then on test prints were sent to the proof lab weekly to constantly get feedback on our model and this was very helpful in tracking progress.

Overall the team really enjoyed the project and further learning about the process of design and prototyping. It was something that proved to be more challenging than what was originally expected at the start.

Appendix

A1: Final User Interface






PRICING
PRICING OPTIONS
MONTHLY SUBSCRIPTION OPTIONS
MATERIAL
COST PER PRINT
PLA
$X
RESIN
$X
MULTI
$X
Type
# of Models
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Bronze
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PLA, RESIN & MULTI
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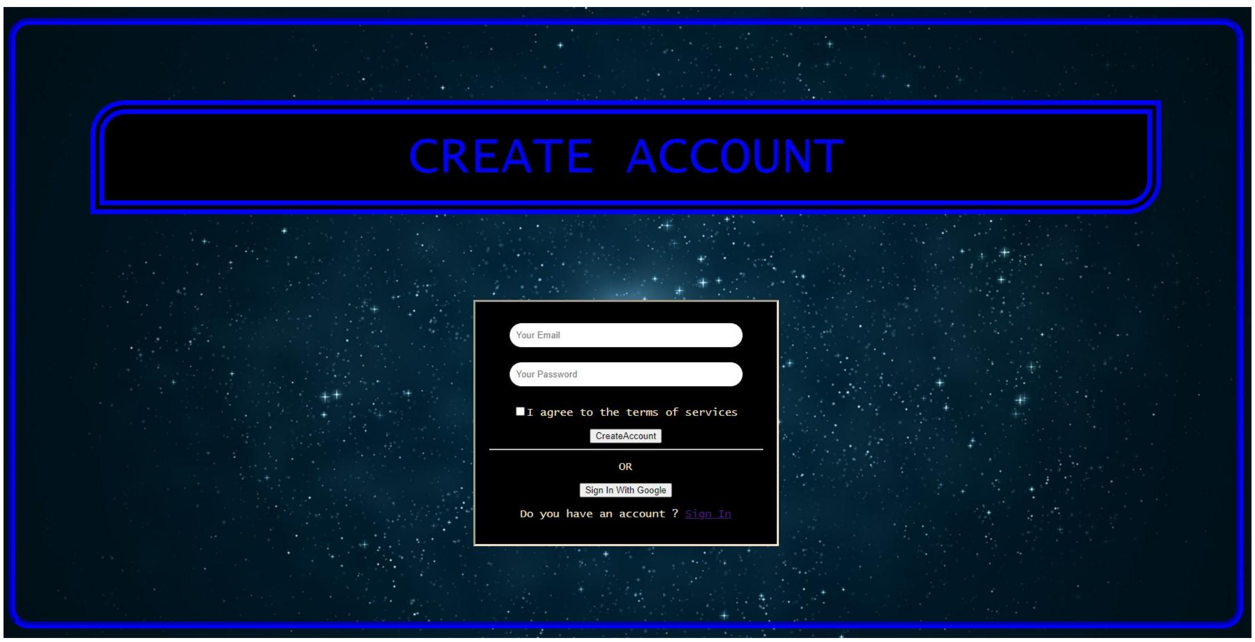
CREATE ACCOUNT
Your Email
Your Password
I agree to the terms of services
CreateAccount
OR
Sign In With Google
Do you have an account ? Sign In

A2: FreeSurfer Automation Code

```
-------- freesurfer-linux-ubuntu18_x86_64-dev-20211020-b964143 --------
Setting up environment for FreeSurfer/FS-FAST (and FSL)
FREESURFER_HOME   /usr/local/freesurfer/7-dev
FSFAST_HOME       /usr/local/freesurfer/7-dev/fsfast
FSF_OUTPUT_FORMAT nii.gz
SUBJECTS_DIR      /usr/local/freesurfer/7-dev/subjects
MNI_DIR           /usr/local/freesurfer/7-dev/mni
nathan@LAPTOP-FF9FC75L:~$ cd /usr/local/freesurfer/7-dev/subjects
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
```

```
nathan@LAPTOP-FF9FC75L:~$ cd /usr/local/freesurfer/7-dev/subjects
nathan@LAPTOP-FF9FC75L:/usr/local/freesurfer/7-dev/subjects$ mris_convert /usr/local/freesurfer/7-dev/subjects/NIFTI01/surf/rh.pial rh.stl
Saving rh.stl as a surface
```

A3: Meshlab Automation Code

```
Brain_Smoothing_UI.py - workspace (Workspace) - Visual Studio Code
duck_triangulate.dae   mesh.py   Brain_Smoothing_UI.py   Release Notes: 1.66.0
MeshLab > Brain_Smoothing_UI.py > ...
```

```python
import PySimpleGUI as sg
import pymeshlab as ml


layout = [[sg.Text("Brain Smoothing Button")], [sg.Button("Smooth")]]

# Create the window
window = sg.Window("Sample UI", layout)

# Create an event loop
while True:
    event, values = window.read()
    # End program if user closes window or
    # presses the OK button
    if event == "Smooth" or event == sg.WIN_CLOSED:
        break
ms = ml.MeshSet()
ms.load_new_mesh('Brain Model.stl')
ms.load_filter_script('Full Brain Script.mlx')
ms.apply_filter_script()
ms.save_current_mesh('Smoothed_Brain_Model.stl')
```

```python
window.close()
```

A4: Meshmixer Automation Code