3D Scanning Applications for Cranioplasty Procedures

Final Report

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Summary

Cranioplasty procedures are typically performed to remove tumors from the brain. As such, this process involves removing a section of the skull in order to access and resect the tumor. However, when concluding this type of procedure, the original skull fragment often cannot be used to fill up the defect. When initially removing the fragment, a large percentage of it turns into bone dust, rendering the fragment unusable. Currently, reconstructive surgeons, like Dr. Gordon, will modify a preoperatively designed implant by trial and error until the defect is covered. The new solution that Dr. Gordon, Dr. Armand, and Ryan Murphy are developing involves identifying the defect using a Polaris optical system and projecting that shape onto a 3D printed implant. The surgeon then tailors the implant to fit the skull using an outline traced using a projection system. While this process may be largely more accurate than the current trial and error procedure, there is significant room for improvement. This project will attempt to implement a handheld 3D scanning system that will reduce the cost and complexity of the projection enhanced modification system.

Background

Cranioplasties, also referred to as secondary cranial reconstructions, usually follow craniectomies administered in the case of severe trauma, stroke, or even brain tumors. The cranioplasty procedure is indicated for "cerebral protection, cosmetic appearance restoration, and treatment of the syndrome of the trephined." For these reasons, the cranioplasty procedure is vital to the quality of life and health of patients. In many cases, however, the bone flap removed during a craniectomy cannot be replaced for a variety of reasons, such as large gaps due to cutting, risk of infection, or even at the surgeon's discretion. For these surgeries, the surgeon will generally use titanium mesh or an implant made of Poly-Methyl Methacrylate (PMMA) to fill the hole.

Recently, surgeons have begun to use Customized Cranial Implants (CCI) made of PMMA, which are fabricated preoperatively using Computer Assisted Design and CT scans of the patient's head. The CT scans allow technicians to design an oversized implant over the region where surgery will be taking place. CCI's provide many benefits to the patient, as well as the surgeon. As Dr. Gordon mentions in his paper, "CCI's provide a full thickness calvarial reconstruction unlike titanium mesh, and may avoid unnecessary dead space underneath." However, these sterile implants must be modified intraoperatively to obtain a perfect fit in the defect.

As seen in the current research being performed by Dr. Gordon, these cranioplasty procedures involving the intraoperative modification of a PMMA CCI can take almost an hour of surgical time. While the benefits of CCI's negate the excessive amount of surgical time, this procedure has much room for improvement. In attempts to improve current procedure times, Dr. Gordon, Dr. Armand, and Ryan Murphy have created a system that implements the Polaris optical tracker and a laser projection system that can project a cut-line onto the CCI. This system is currently being tested, but shows promising initial results in decreasing overall operation time and helping the reconstructive surgeon make more precise first cuts. While minor modifications may still be required, the general guidance already helps significantly in reducing the amount of time spent by the surgeon for making modifications.

While the implementation of the Polaris system is already a huge step forward, there are some drawbacks to the current system. The Polaris optical tracking system, while highly accurate, is very expensive and difficult to set up. The Polaris tracking system can also only measure points using a large rigid fixation on the skull of the patient and an unwieldy, optically tracked pointer. One major issue with this pointer based identification system is that it is difficult to collect points describing the various angles and shapes of the cranial defect. Currently, the point clouds that are obtained lack any information about the slanted sides of the defect.

With the advent of highly accurate, handheld 3D scanners, it is possible to create a system that is portable and that offers more information to the projection system and the surgeon. Using a tablet based scanner would provide a much cheaper and easier to use solution than the Polaris based defect identification process. This project proposes to develop the necessary algorithms and technological pipeline required for a 3D Scanner based system, which should simplify, as well as speed up, the cranioplasty procedure.

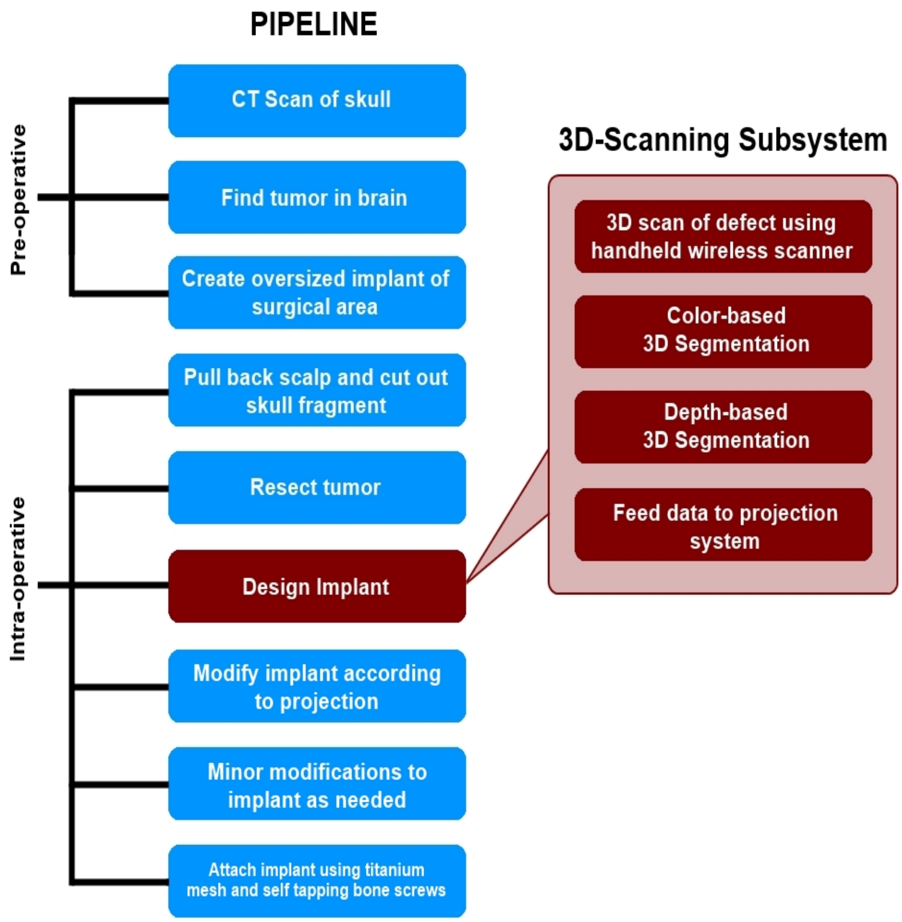
Procedure Outline

This project proposes to integrate a new subsystem into the cranioplasty pipeline for scanning the defect created during the procedure and the generation of a 3D mesh model that accurately describes the defect. First the surgeon acquires a preoperative CT scan of the patient's head. Using this scan, the tumor is located and a customized cranial implant (CCI) is created. It should be noted that the CCI initially covers a greater area than the expected defect size. The implant will be shaped down to the proper size during the operation, using the new 3D-scanning enhanced subsystem as a guide.

The surgeon begins the procedure normally by pulling back the scalp, marking the surgical area with a sterile surgical pen, and cutting out the skull fragment. Once the tumor is then removed from the brain, the cranial reconstruction process begins. With this new subsystem in place, the surgeon or nurse will use a handheld, wireless device to take a 3D scan of the defect. Note that for this project, we will be using an iPad mounted with a Structure Sensor as the "handheld scanner." When scanning the defect with this device, the operator should hold the scanner within half a meter of the defect for the most precise measurements. Scanning should be done by pointing the sensor towards the defect at some arbitrary starting position, and then slowly moving it around the site until the scanner indicates the operator to stop. The built-in software for this scanner is very responsive in that it will notify the user to slow down, back up, or move to a previous location when needed.

Once the scanning is complete, the data is wirelessly uplinked to a computer where final rendering and colorizing takes place. Once a final mesh has been created, the program will begin attempting to identify the general region of the defect using a color-based segmentation. The segmentation algorithm will focus on markings around the surgical area made with the sterile surgical pen. This thick outline remains around the defect even after removal of the skull fragment, since the cut is smaller than the marked area. The results of this segmentation algorithm will be used to trim the 3D mesh file down to just the defect. The program then runs a depth-based segmentation algorithm that will calculate the depth and angle of the edge cuts. This is crucial information for the surgeon to have so he is able to make an accurate cut of the CCI. If this initial cut is more accurate, overall surgical time will be reduced by decreasing the time taken thereafter to make additional adjustments to the implant. A more accurate initial cut will also reduce the likelihood of gaps between the implant and the skull. Once the segmentation is complete, the mesh is then sent to a laser projection system. The image of a cut is overlaid onto the CCI, allowing the surgeon to cut the implant down to the proper size and fit. Once the initial cuts are made, the surgeon can try the implant on the defect and make minor modifications as needed. Finally, the implant is secured onto the defect with titanium mesh and self tapping bone screws

Procedure Pipeline



Procedure Evaluation

The new procedure will be evaluated using the following metrics:

1. Time:
   The current, manual implant modification procedure used by Dr. Gordon takes by far the most amount of time in the operating room. This process was improved upon by Ryan Murphy's work, which uses the Polaris Optical Tracker to determine the shape of the defect and a projection system to assist with cutting. The new procedure defined in this proposal should be able to further reduce time in the operating room. The 3D scanning applications do not require preoperative set up of an Optical Tracking system and do not require rigid fixations on the skull of the patient.

2. Accuracy
   The 3D scanning applications in this procedure should be able to maintain an accuracy of close to 1 mm. 1 mm accuracy is what the current Optical Tracking system is able to achieve and would provide surgical level of accuracy for future Computer Controlled Cutting machines that could potentially be implemented at a later time. The documentation for the scanner that will be used in this procedure does maintain 1mm accuracy when placed within .5 meters of the patient.

3. Ease of Use
   While there are no quantitative metrics to determine any improvements in this metric, ease of use should be simple to determine qualitatively. The 3D scanning procedure, if successfully developed, should be remarkably easier to use than the manual modification procedure used currently. Handheld 3D scanning should prove to be remarkably easier to implement, since the devices involved are significantly smaller and simpler to use. If a fully integrated 3D scanning application is developed, a surgical technician may not even be required during the operation.

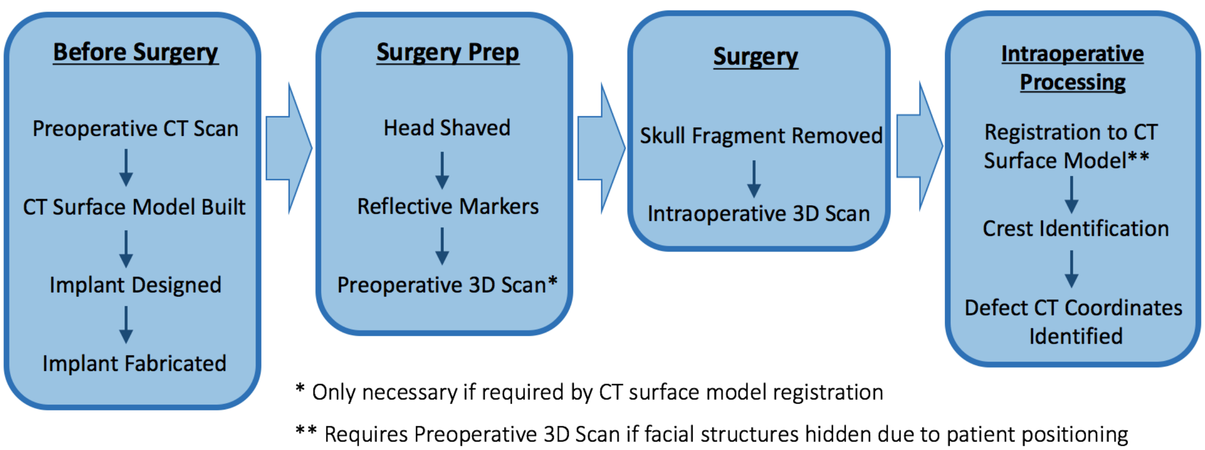
4. Cost
   The proposed procedure should cost less than $2,000 to implement, including a reusable iPad, sensor, and workstation for final rendering, and all components are reusable. Implementation of such a system would also provide a significant reduction in surgical time, therefore reducing the overall cost of the cranioplasty procedure.

Problem

While the Structure Sensor can capture a detailed surface model intraoperatively, heavy post processing is required for this imaging to be useful to the surgeon. To create a more accurate implant, the coordinates of the cranial defect must be identified in CT Scan coordinates, the space where the fabricated implant was designed. This requires defect wall identification as well as registration to the CT scan coordinate system. Once these points have been identified, this information can be passed to a CNC Milling machine or laser guidance system for more accurate implant modification.

Approach

The approach to the problem can be summarized in the steps below.



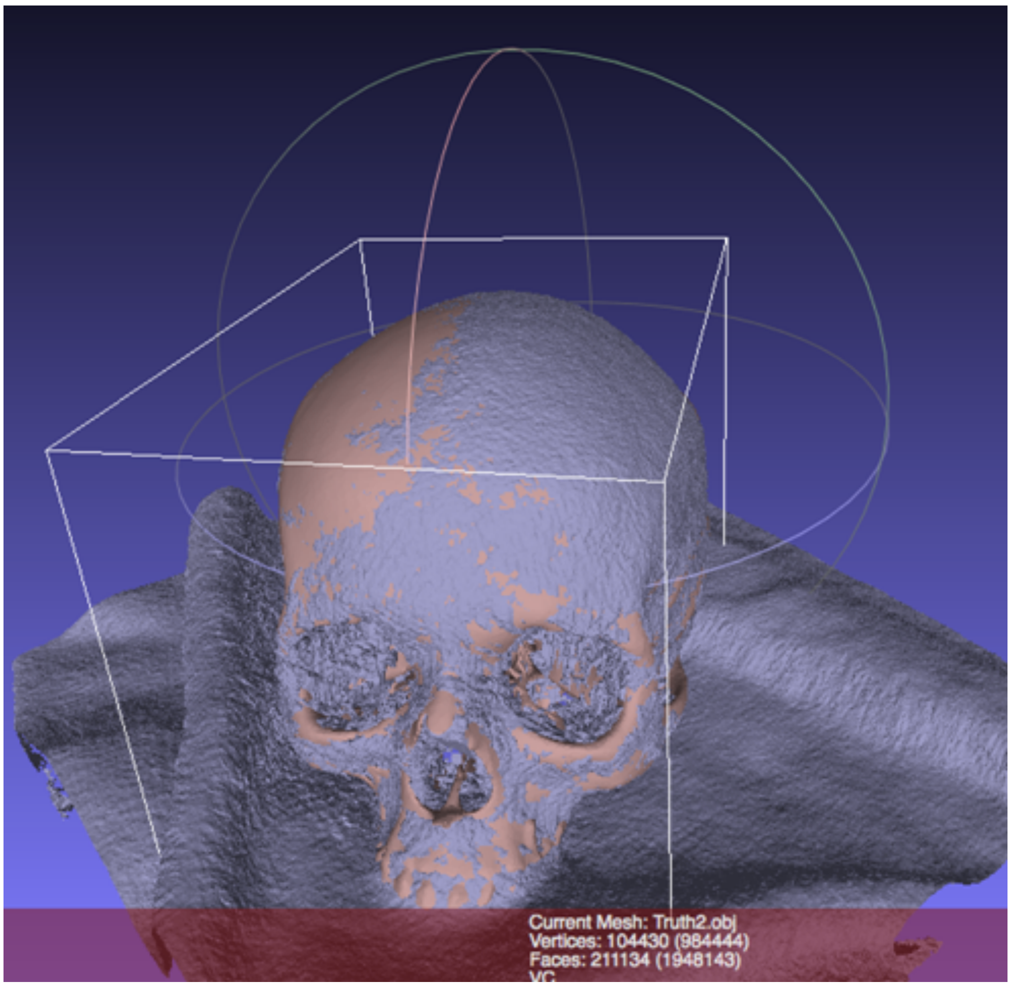
The two potential steps of registration are IR Model to CT Model, which occurs in each case, and IR Model to IR Model, which occurs only with certain patient positions. IR Model to CT Model registration is achieved using certain bony structures of the skull while the IR Model to IR Model registration is done through Color Dot registration. The color dots serve as fiducials for fast gross registration, and both registrations are further refined using ICP.

The second stage of processing is the identification of the walls of the defect. This system will take an input of the centroid of the defect, and will output a point cloud describing the shape and orientation of the defect. Using previously defined registrations, these points will be related to points in the CT space. From here these points can be passed to a laser guidance system or an automated CNC Milling Machine.

Results

Surface Model to CT Scan Registration

The IR Surface model was registered to the CT Surface model great accuracy. The result of the registration is shown below, where both models are overlaid on each other. The average reported error between the two models after transformation was approximately .443 millimeters. This is well below the expected accuracy of approximately 1 millimeter.

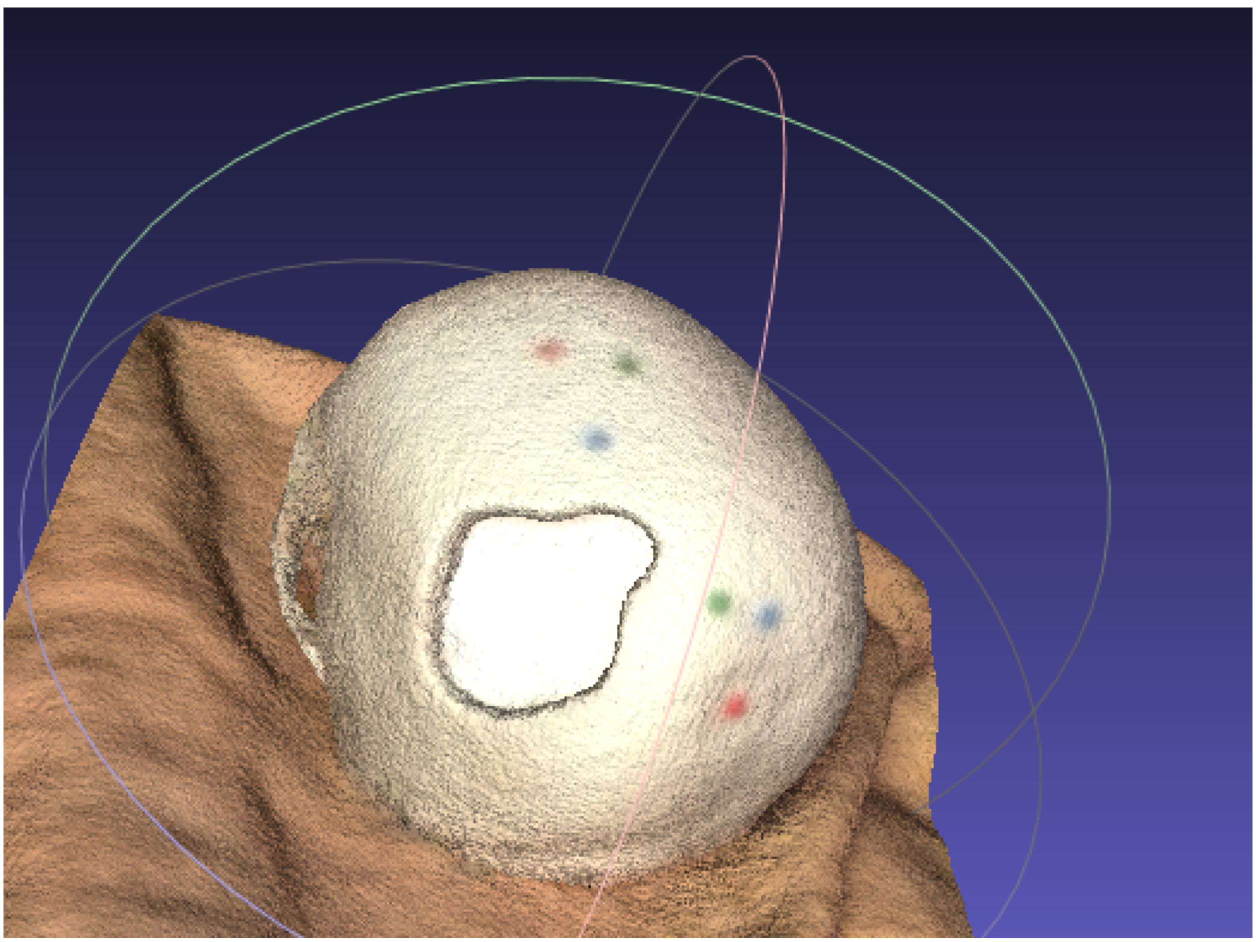


While there was some initial success with ICP this process was completed manually, and will be automated in future iterations of this scanning pipeline.

Color Dot Registration

Below is an image of two surface models overlaid after using color dots to obtain a registration and ICP to refine this registration. The color dots were first identified using their HSB values from vertex color information. Once these vertices were identified, a cluster analysis was completed to separate the two dots of each color. The points were identified by using the relative distances to dots of particular colors, such as the distance from red to green in pattern group A and the distance from red to green in patter group B.

Once points in the first surface model were identified and associated points in the second surface model were identified, Horn's method was used to calculate a transformation between the 6 centroids of each colored dot.

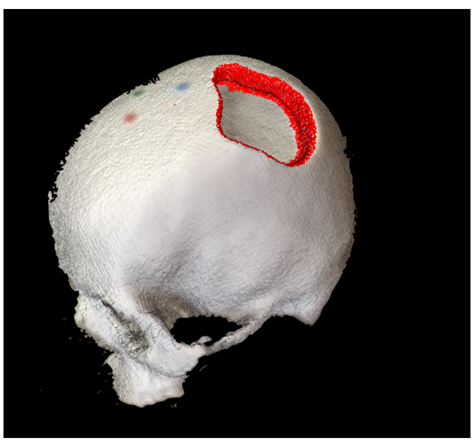


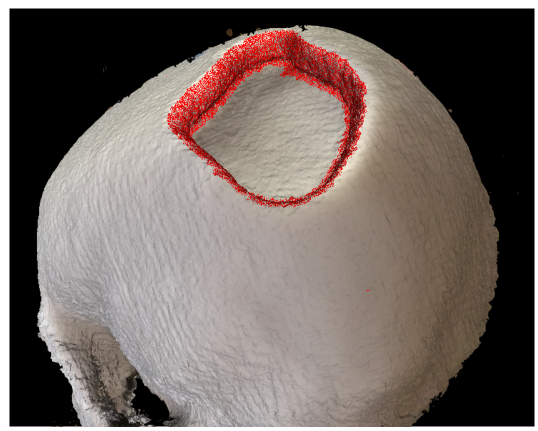
This color dot transformation provided a gross registration of the two surface models, and the registration was further refined using ICP.

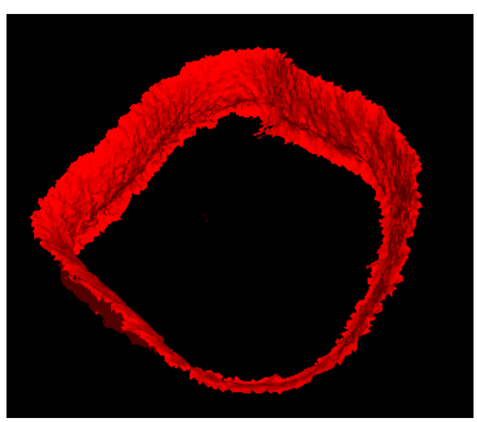
Defect Wall Detection

To determine the defect wall from the surface model, a directional filter and a neighbor based scoring system is used. The details of these two processes will be described in a later section of this paper, but the general idea of the algorithm is as follows. We first want to throw away excess points that obviously cannot be vertices on the wall, i.e. the horizontal smooth surfaces of the skull/brain. This is done by using the directional filter to discard points whose normal vectors point away from a pre-determined centroid. Then, the remaining points will go through a scoring system. This system will take each point and calculate the angle between the point's normal vector and the centroid normal vector. If this angle is above a certain "hard" threshold, then it will immediately include the point. Otherwise, the point will go through an additional scoring system that uses "rings of neighbors" to help determine whether a point should be included or not. This is necessary because there are no sharp edges; instead, the edges are all gradual due to assumptions made during the scanning process.

The following images show the results of our algorithm, which appears to work quite well. Testing will continue and the parameters of the algorithm will keep improving as we are able to gather more test data.







Significance

The modules developed as a part of this project are significant because they make major steps towards a completely automated implant modification system. Key hurdles in the design of such a system are the registration steps and the defect wall identification steps. These have been solved by using the large number of points for more accurate registration and the Neighbor Based Scoring Algorithm. These two developments solve some of the major imaging issues in an automated cranioplasty implant modification system.

Management Summary

Proposed Deliverables

Minimum

- Developed algorithms for defect identification on test objects
    - Implementation of a color and depth based segmentation algorithm
    - Creation of a mesh refocusing algorithm to narrow search field
- Paper regarding color and depth based segmentation for defect detection on 3D scan

Expected

- Integration into the cranioplasty surgical procedure
- Ability to use the scanner in an uplink mode to workstation

Maximum

- Tablet application with integrated 3D scanning and processing
- Testing in the Mock Operation room

Actual Deliverables

- Developed algorithms for defect identification on test objects
    - Implementation of a color and depth based segmentation algorithm
    - Creation of a mesh refocusing algorithm to narrow search field
- Paper regarding color and depth based segmentation for defect detection on 3D scan
- Integration into the cranioplasty surgical procedure
- Ability to use the scanner in an uplink mode to workstation
- Testing in the Mock Operation room

Unmet Deliverables

- Paper regarding color and depth based segmentation
    - To be completed in detail over summer of 2015
- Tablet application with integrated 3D scanning and processing
    - To be completed as a workstation application over summer of 2015

Division of labor

Majority of development was split equally over the course of the semester. Color segmentation and registration were completed by Alex Mathews. Neighbor Base Scoring Algorithm was completed by Joshua You.

Dependencies:

Status	Dependency	Description
Completed	Structure Sensor	Sensor to be used for 3D imaging, provided by Dr. Armand
Completed	iPad	iPad for mounting the sensor, will use personal iPad
Completed	Test Object	Printed at the Digital Media Center
Completed	Phantom Skull	Provided by Dr. Armand
Completed	Mock Operations	Will take place with Dr. Gordon at JHMI once a month

All dependencies have been resolved prior to the start of the development process.

Milestones:

Expected Date	Milestone	Completion Date
Feb 18	Completed project proposal	Feb 18
Feb 28	Color segmentation algorithm completed	Feb 28
Mar 14	.obj area of interest algorithm completed	Mar 14
Mar 28	Phantom skull testing	Mar 28
Apr 4	Mock Operation: Test scans of surgical environment	Apr 4
Apr 9	Checkpoint Presentation	Apr 2
Apr 18	Complete procedure integration modules	TBD Summer 2015
May 2	Mock Operation	TBD Summer 2015
May 8	Poster Session	May 8

Future Plans

This project will continue over the summer of 2015. The primary goals of this continuation are to complete a fully functioning, validated application that handles all the imaging and segmentation required for more precise implant modification. The two key subprojects are:

1. IRB Approved Study: The IRB approved study will validate the scanner's use in a surgical environment. One key aspect of the scanning process to be studied is the ability to obtain accurate registrations of scanner data to CT data. The study will also qualitatively analyze the ease of use for the surgeon, specifically focusing on the scanner's portability and size.

2. Application Development: The application will be developed as a module for 3D slicer. This module will import a surface model generated from a CT scan and surface models from the 3D IR scanner. The application will segment the IR based models for the walls of the defect after taking in centroid information. The application will then calculate the transformations required to register the IR models to the CT models, and finally the program will yield a set of points describing the shape and size of the defect in CT coordinates. This information can be passed to a laser guidance system or a CNC Milling Machine.

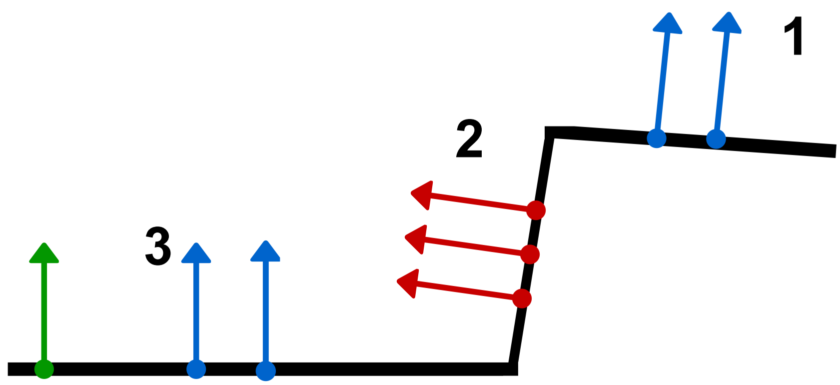
These subproject should be completed by the Fall of 2015. In addiction, a paper regarding a general form of the Neighbor Based Scoring System and Directional Filtering Algorithms will be written for journal publication.

<u>Technical Summary:</u> Defect Wall Detection

The wall detection algorithm is divided into two distinct steps.

Directional Filtering

First, a directional filter is applied to the vertices with the intent to discard as many points as possible that are not a part of the wall. This is done by first defining a centroid and determining its normal vector based on the surrounding triangles. Additionally, every vertex is also assigned a normal vector that is calculated by averaging the normal vectors of the triangles that include the point. Given these normal vectors, the vertices are then put through the directional filtering, which will throw away points that have normal vectors that point away from the centroid. In the figure below, the filter will throw away the blue arrows labelled (**1**).



Neighbor Based Scoring System

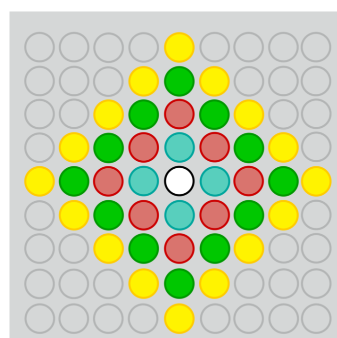
After applying the filter, the second step is to determine which vertices make up the wall of the defect. To determine this, the rest of the points are processed through a neighbor based scoring system that will help determine whether a vertex should be included or not. This final step will be able to capture all points that are a part of the wall (**2**), and discard the remaining points (**3**).

For each of the remaining points, the algorithm will first find the angle between the point's normal vector and the centroid normal vector. If this angle is above a certain "strong" threshold, then it will automatically be included. Otherwise, the point, then, will go through an additional scoring system. This scoring system uses "rings of neighbors" around the vertex in question to determine if it is a wall point; each ring will be factored into a percentage of the final score. The weight of each ring increases inversely to the distance away from the point. Based on this final score, the algorithm will determine if the point should be included or not. The pseudocode is as follows:

```
for each point in all_points do
   /* "Hard" threshold, will automatically include point */
   if ( angle_between(center->normal, point->normal) > A )
       save_points <- point
   else
       /* Scoring Algorithm: 4 Rings of Neighbors */
       for each n1 in point->neighbor_points do
           if ( angle_between(center->normal, n1->normal) > B )
               score1 <- score1 + 1
           for each n2 in n1->neighbor_points do
               if ( angle_between(center->normal, n2->normal) > C )
                   score2 <- score2 + 1
               for each n3 in n2->neighbor_points do
                   if ( angle_between(center->normal, n3->normal) > D )
                       score3 <- score3 + 1
                   for each n4 in n3->neighbor_points do
                       if ( angle_between(center->normal, n4->normal) > E )
                           score4 <- score4 + 1
                   total4 <- total4 + (number_of_n4_points_checked)
               total3 <- total3 + (number_of_n3_points_checked)
           total2 <- total2 + (number_of_n2_points_checked)
       total1 <- total1 + (number_of_n1_points_checked)

       score = F * (score1 / total1) + G * (score2 / total2) +
               H * (score3 / total3) + I * (score4 / total4)

       if score > J
           save_points <- point
```

The thresholds and weights used will vary, depending on what this algorithm will be used for. For this project, we used the following thresholds and weights (note: threshold units are in degrees):

```
A = 55, B = 10, C = 20, D = 30, E = 40

F = .2, G = .3, H = .9, I = .9

J = .7
```



The number of neighbor rings can also change based on the situation, but the idea still holds. Ideally, when we do create the module for this, all these variables will have a corresponding slider, which will enable the user to dynamically change the thresholds and weights as he or she sees fit.

References

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2. Gordon CR, Fisher M, Liauw J, Lina I, Puvanesarajah V, Susarla S, Coon A, Lim M, Quinones-Hinojosa A, Weingart J, Colby G, Olivi A, Huang J. Multidisciplinary Approach for Improved Outcomes in Secondary Cranial Reconstruction: Introducing the Pericranial-Onlay Cranioplasty Technique. Neurosurgery. 2014 Jun;10 Suppl 2:179-89.

3. Cates JE, Lefohn AE, Whitaker RT. GIST: an interactive, GPU-based level set segmentation tool for 3D medical images. Med Image Anal. 2004 Sep;8(3):217-31.

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