Validating and Improving Single-Stage Cranioplasty Prosthetics with Ground Truth Models

Checkpoint Presentation

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Introduction

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Mentors: Mehran Armand, Chad Gordon, Ryan Murphy

Affiliations:

1. Applied Physics Laboratory: Research and Exploratory Development Department
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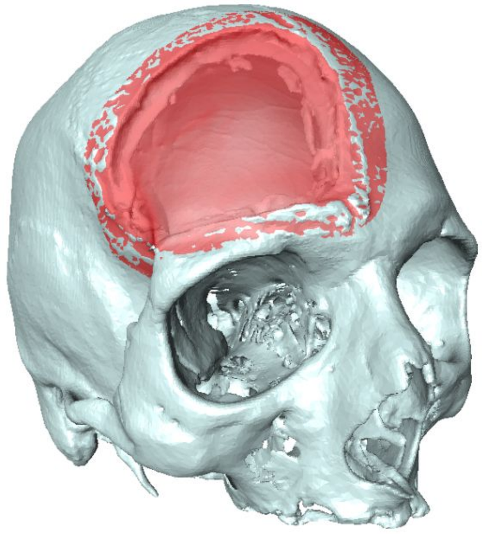
4. Johns Hopkins University School of Medicine: Department of Neurosurgery

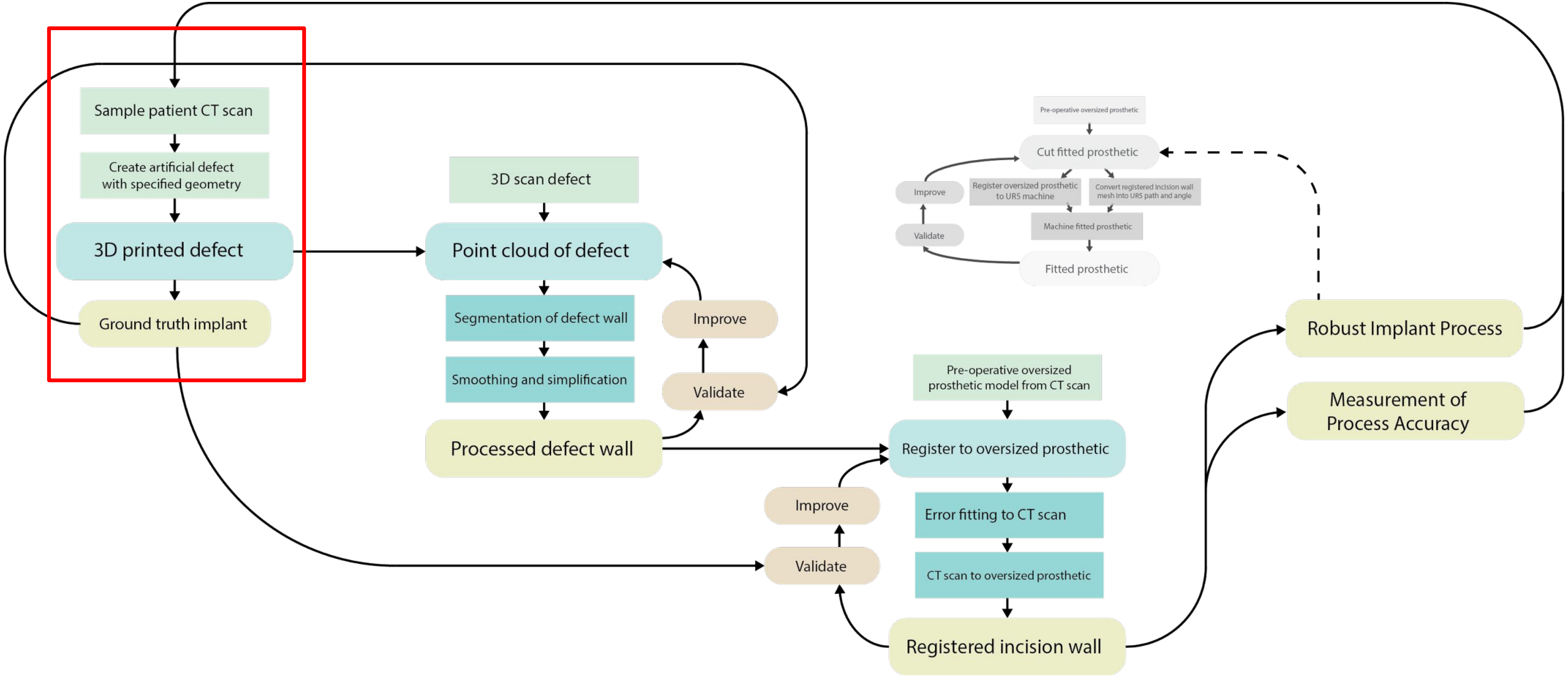
Background

- Creating a prosthetic that perfectly fits the operative hole requires the patient to be brought back to the operating room at a second date (two-stage surgery).
- A single-surgery solution where the implant is created manually can take considerable amount of time (10 - 80 minutes) and be inaccurate.
- New methods that use an overhead projector to aid manual implant creation are limited by complexity of implant.
- System has been developed for using 3D scanner to create a machined single-stage implant, but...

- **Effectiveness of using 3D scanners and point cloud models to completely capture defect shape and bevel and register it to patient space is currently unknown.**



Technical Approach



Deliverables

- Minimum
  - Segment and process point cloud of defect to create defect mesh
  - Register defect mesh to patient
  - Register mesh to oversized prosthetic
- Expected
  - Create ground truth models
  - Validate and improve process accuracy
  - Quantify accuracy of implant creation
  - Package process as Slicer module
- Maximum
  - Test process with cadavers
  - Register oversized prosthetic to UR5 machine
  - Define UR5 path for cutting fitted prosthetic

Updated Deliverables

- Minimum - Completed
  - ~~Segment and process point cloud of defect to create defect mesh~~
  - ~~Register defect mesh to patient~~
  - ~~Register mesh to oversized prosthetic~~
- Expected - In Progress
  - Create ground truth models
  - Validate and improve process accuracy
  - Quantify accuracy of implant creation
  - Package process as Slicer module
- Maximum - Modified
  - Test process with cadavers
  - ~~Register oversized prosthetic to UR5 machine~~
  - Define UR5 path for cutting fitted prosthetic

Dependencies

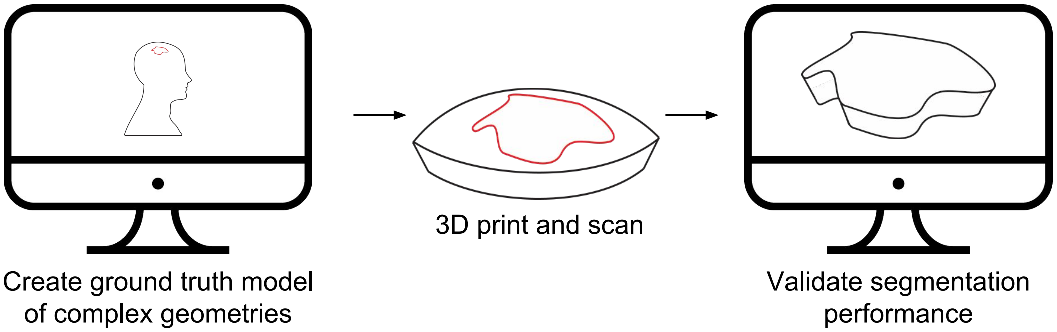
Status	Dependency	Description
Completed	Structure Sensor	Sensor to be used for scanning incision site. Provided by Dr. Armand.
Completed	iPad	iPad to use with structure sensor. Provided by Dr. Armand.
Completed	Software Repository	Provided by Ryan Murphy. Contains existing lab code, system, and test data.
Completed	Patient CT Scans	Will be used to create ground truth models. Provided by Ryan.
On Hold	3D Printer	Needed to fabricate ground truth models. DMC, BME Design Studio, or Shapeways.
In Progress	Operation Observation	Currently scheduling operation viewing to better motivate understanding of the problem.
On Hold	UR5 Machine	Machine for fabricating prosthetic. Not current priority.

Progress

1. Segmentation
   a. Challenges
   b. Creating test cases
   c. Validation
   d. Alternative method
2. Registration
   a. Approach
   b. Challenges
   c. Future work

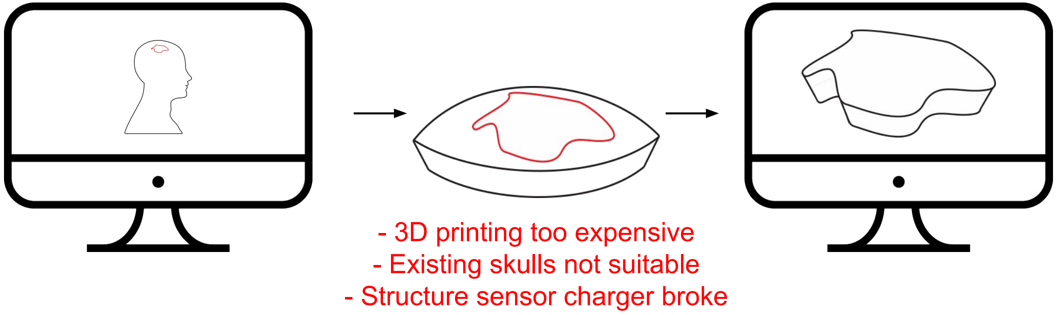
Segmentation

Proposed method:



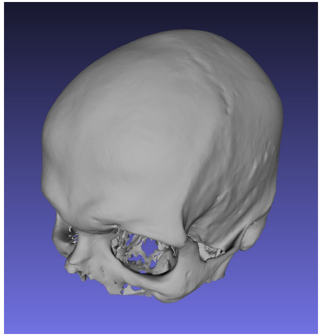
Segmentation

Challenges:

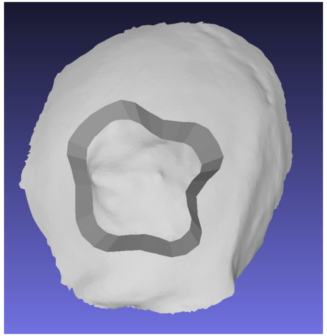


Segmentation

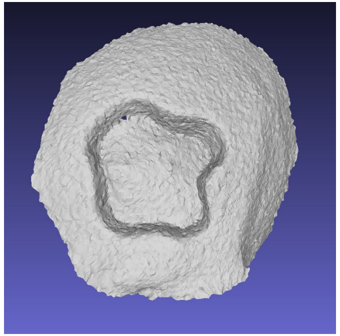
Solution: Simulate test data



Patient skull model

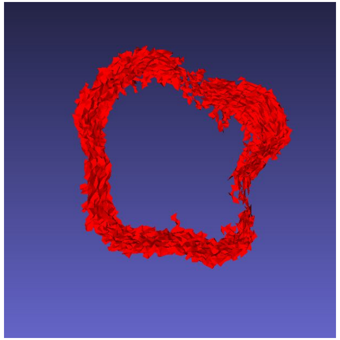


Defect with defined geometry



Noise and smoothing introduced

Segmentation applied

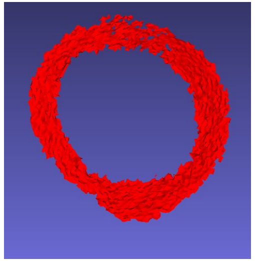
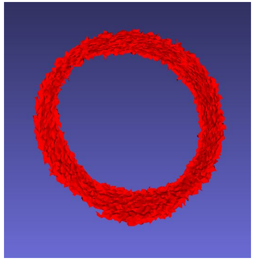
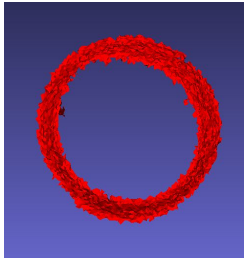
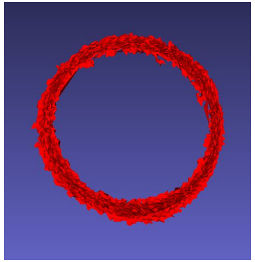
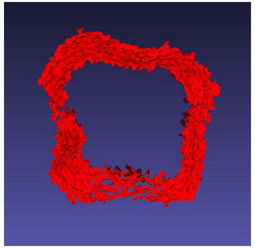
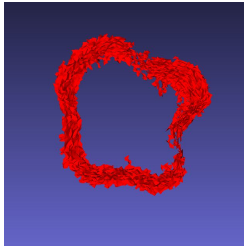
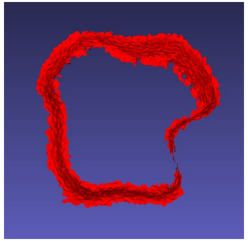
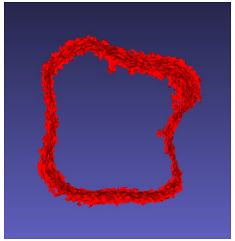


Segmentation cleaned and evaluated

(Random 1mm error with smoothing of edges quantitatively and qualitatively matches scanned data)

Segmentation

Results:

	45°	60°	70°	80°	90°
Regular					
Irregular					

Registration: Initial Approach

Globe fitting

- **Objective:** Translate defect mesh to the skull mesh surface to allow more accurate and easily adjusted initial guesses.
- **Implementation:** Provide basic fitting of the defect mesh to the skull mesh by bounding them against spheres. Compute translation of spheres to origin and transform point clouds.

Iterative Seeding

- **Objective:** Provide multiple initial guesses for the ICP registration of the defect to the skull.
- **Implementation:** Split rotations about each axis in N equidistant segments. Iterate through every combination of rotation about each axis ($O(N^3)$ time) and return the transformation that yields the lowest Root Mean Squared error.

Translation matrix

$$\begin{bmatrix} 1 & 0 & 0 & dx \\ 0 & 1 & 0 & dy \\ 0 & 0 & 1 & dz \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x + dx \\ y + dy \\ z + dz \\ 1 \end{bmatrix}$$

X-axis

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta & 0 \\ 0 & \sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

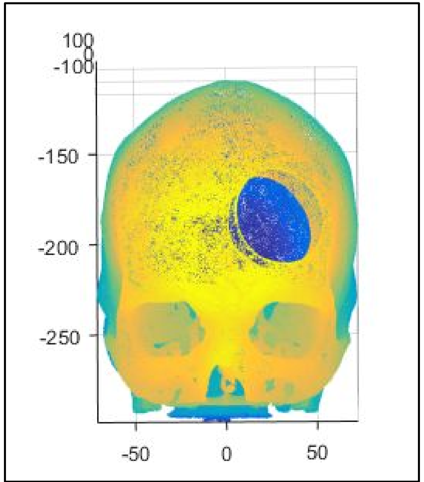
Y-axis

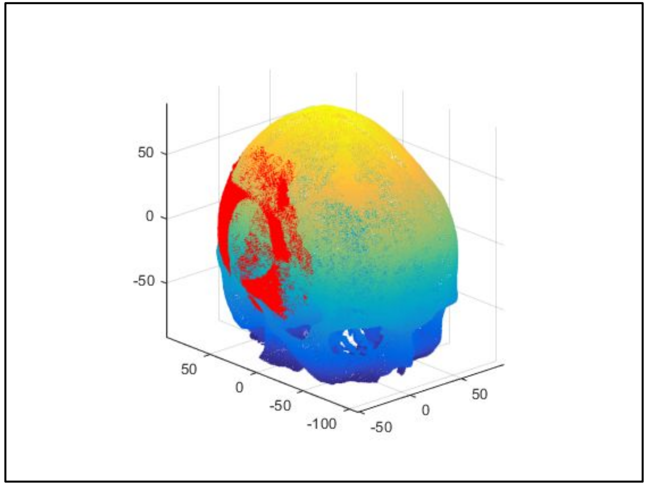
$$\begin{bmatrix} \cos\theta & 0 & \sin\theta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\theta & 0 & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

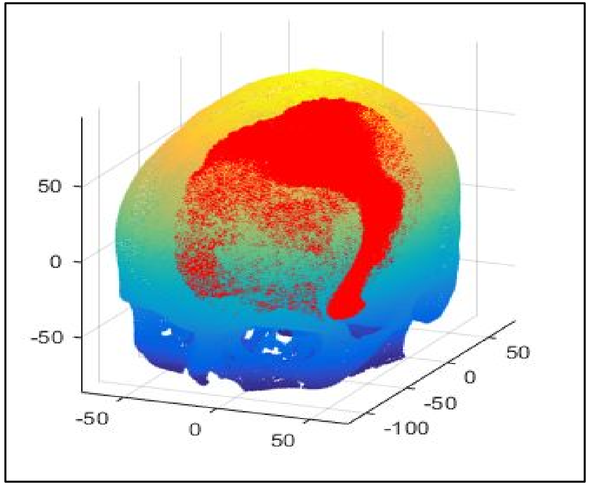
Z-axis

$$\begin{bmatrix} \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Registration: Initial Approach Results







Original Defect Location
(Bevel angle is not accurate in image)

ICP Results;
RMS Error: 2.0774

Manual Input;
RMS Error: 2.8559

Registration: Challenges and Issues

- Lots of local minima
- The global minimum found with a low amount of iterations is often incorrect.
    - Need more resolution but risk of computation time runaway is significant. O(N^3) run time.
- Skull is symmetrical
- How to determine best initial seed for ICP
- Globe fitting may not be sufficient for mesh movement

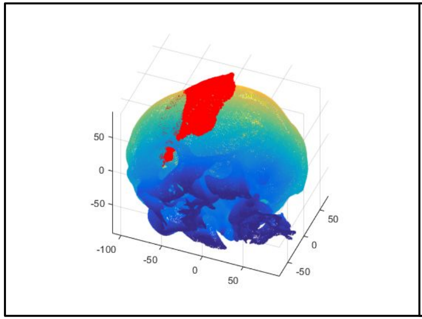
Registration: Current Approach

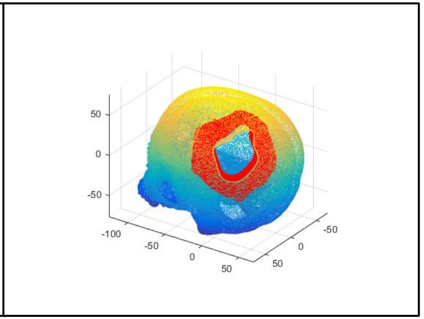
Globe Fitting remains for mesh alignment despite issues with more specific geometries.

Initial Input Perturbations

- **Objective:** Avoid global minimum issue with iterative seeding via manual insertion of approximation. Initial insertion is then perturbed until lowest error in area is found.
- **Implementation**
  - An initial guess by user is computed and a rotation is computed on the point cloud.
  - The x-, y-, and z-axis are sectioned off inside +/-15 degrees rotations - again an $O(N^3)$ runtime, but smaller N required, as minute perturbations on initial guess.
  - Lowest RMS error among perturbations is returned as transformations.

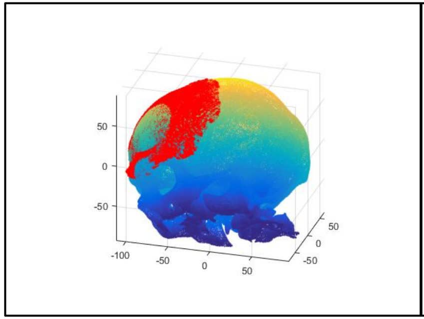
Registration: Current Approach Results

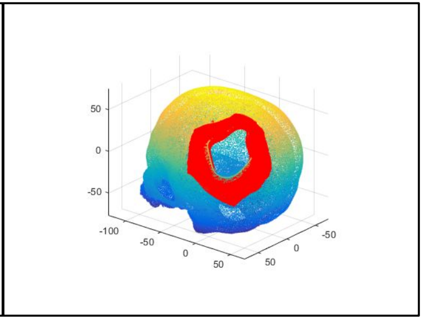




RMS Error: 1.7328
Regular 60 Degree Bevel

RMS Error: 1.7672
Irregular 90 Degree



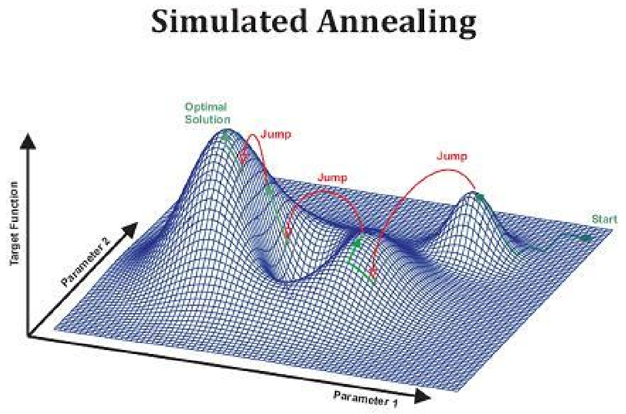


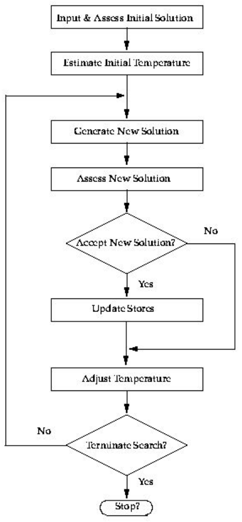
Initial seeding locations

After Initial Value Perturbed ICP

Registration: Future Work

- Simulated Annealing
  - Probabilistic technique for approximating global maximum and minimums.
- Increased features. Possibly texture, curvature or surface normals.
- Use of oversized defect data which is preregistered to the CT space.
  - Significantly decreases the surface area to run ICP in.





Timeline

Date	Objective
2/15 - 3/14	Testing Data Production and Planning
2/22 - 4/25	Registration and Segmentation Development
3/14 - 5/02	Accuracy Testing
4/25 - 5/9	Cadaver and Patient Matching

Timeline

Date	Objective
2/15 - 3/26	Testing Data Production and Planning
2/22 - 4/25	Registration and Segmentation Development
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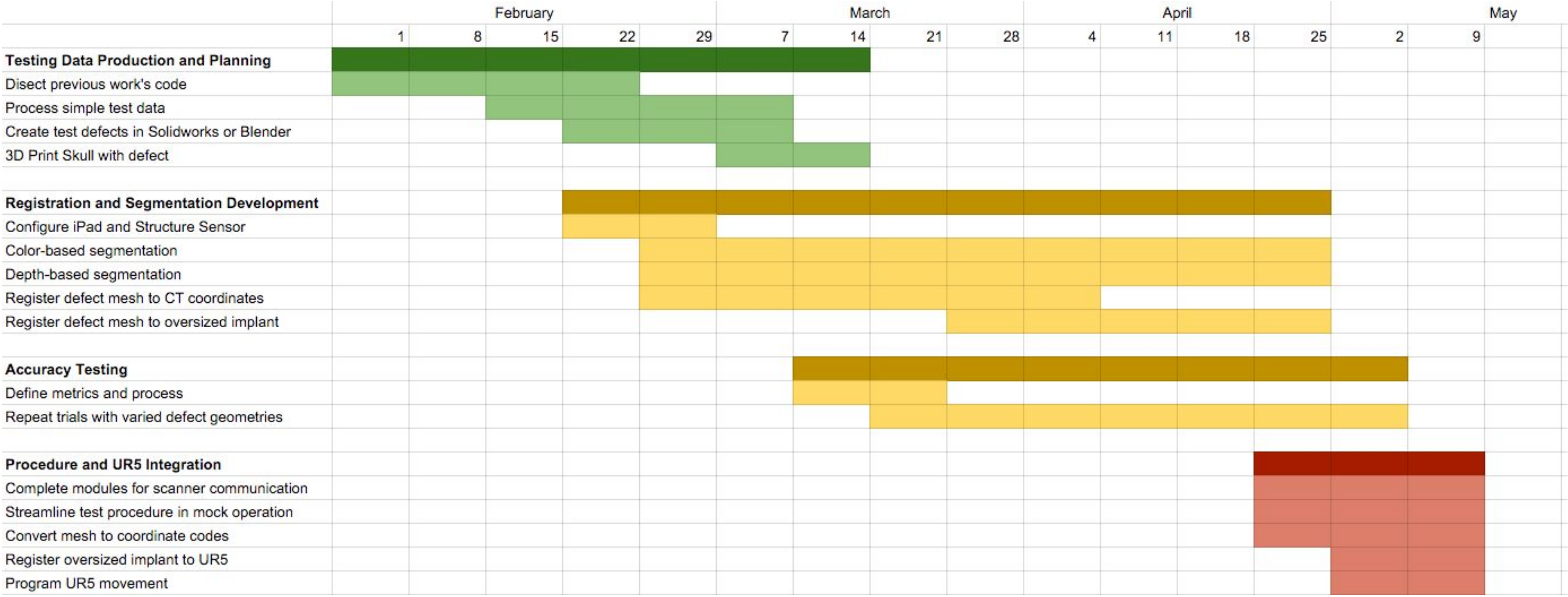
4/25 - 5/9	Cadaver and Patient Matching

Chart


February
March
April
May
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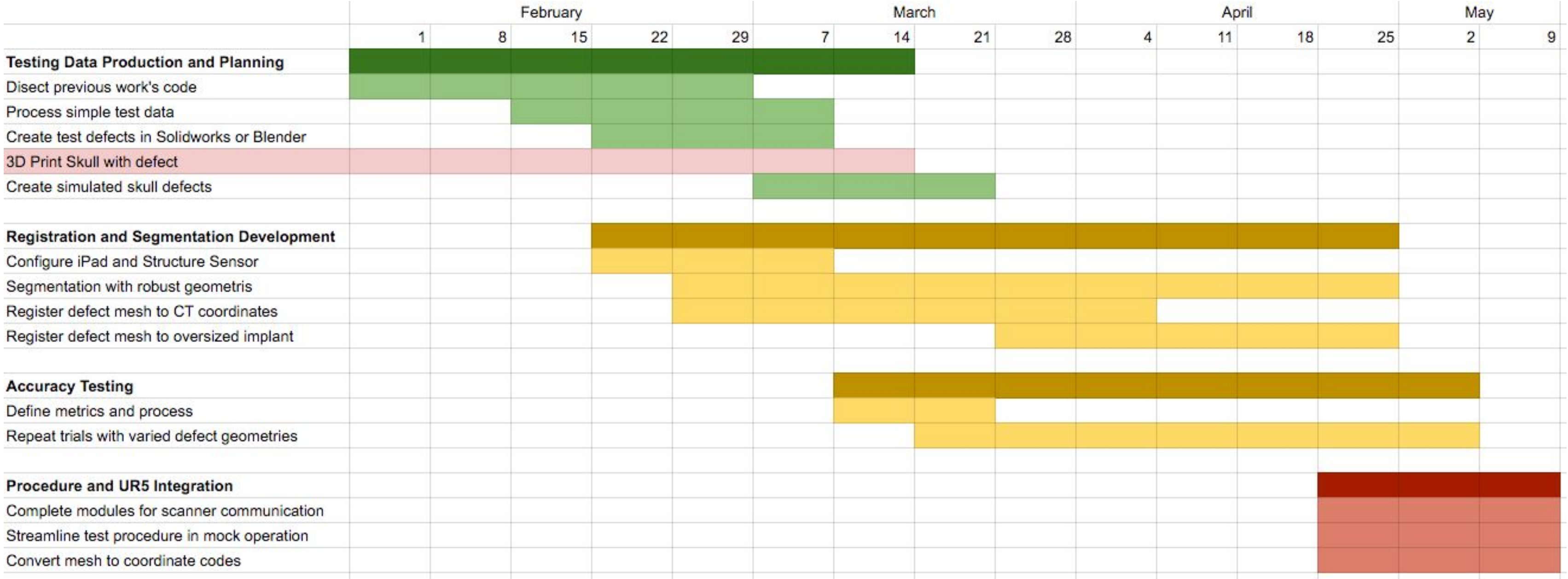
9
Testing Data Production and Planning
Disect previous work's code
Process simple test data
Create test defects in Solidworks or Blender
3D Print Skull with defect
Registration and Segmentation Development
Configure iPad and Structure Sensor
Color-based segmentation
Depth-based segmentation
Register defect mesh to CT coordinates
Register defect mesh to oversized implant
Accuracy Testing
Define metrics and process
Repeat trials with varied defect geometries
Procedure and UR5 Integration
Complete modules for scanner communication
Streamline test procedure in mock operation
Convert mesh to coordinate codes
Register oversized implant to UR5
Program UR5 movement

Updated Chart



Readings

1. 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.

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.

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4. Huang GJ, Zhong S, Susarla SM, Swanson EW, Huang J, Gordon CR. Craniofacial Reconstruction with Poly (Methylmethacrylate) Customized Cranial Implants. The Journal of Craniofacial Surgery. 2015 Jan;26(1):64-70.

5. Murphy RJ, Wolfe KC, Gordon CR, Liacouras PC, Armand M, Grant GT. Computer-assisted Single-stage Cranioplasty. IEEE. Jan 2015.

Questions?