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
2. Johns Hopkins University: Department of Mechanical Engineering
3. Johns Hopkins University School of Medicine: Department of Plastic and Reconstructive Surgery
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

**Introduction**

- Sample patient CT scan
- Create artificial defect with specified geometry
  
- **3D printed defect**
  
- Ground truth implant

**Background**

- 3D scan defect
- Point cloud of defect
- Segmentation of defect wall
- Smoothing and simplification
  
- Processed defect wall

**Deliverables**

- Improve
- Validate

**Progress**

- Pre-operative oversized prosthetic
- Cut fitted prosthetic
  
- Robust Implant Process
- Measurement of Process Accuracy
  
- Error fitting to CT scan
- CT scan to oversized prosthetic

**Timeline**

- Registered incision wall

**Readings**
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

<table>
<thead>
<tr>
<th>Status</th>
<th>Dependency</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Completed</td>
<td>Structure Sensor</td>
<td>Sensor to be used for scanning incision site. Provided by Dr. Armand.</td>
</tr>
<tr>
<td>Completed</td>
<td>iPad</td>
<td>iPad to use with structure sensor. Provided by Dr. Armand.</td>
</tr>
<tr>
<td>Completed</td>
<td>Software Repository</td>
<td>Provided by Ryan Murphy. Contains existing lab code, system, and test data.</td>
</tr>
<tr>
<td>Completed</td>
<td>Patient CT Scans</td>
<td>Will be used to create ground truth models. Provided by Ryan.</td>
</tr>
<tr>
<td>On Hold</td>
<td>3D Printer</td>
<td>Needed to fabricate ground truth models. DMC, BME Design Studio, or Shapeways.</td>
</tr>
<tr>
<td>In Progress</td>
<td>Operation Observation</td>
<td>Currently scheduling operation viewing to better motivate understanding of the problem.</td>
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</tbody>
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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:

- Create ground truth model of complex geometries
- 3D print and scan
- Validate segmentation performance
Segmentation

Challenges:

- 3D printing too expensive
- Existing skulls not suitable
- Structure sensor charger broke
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:

<table>
<thead>
<tr>
<th></th>
<th>45°</th>
<th>60°</th>
<th>70°</th>
<th>80°</th>
<th>90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular</td>
<td><img src="regular_45.png" alt="Image" /></td>
<td><img src="regular_60.png" alt="Image" /></td>
<td><img src="regular_70.png" alt="Image" /></td>
<td><img src="regular_80.png" alt="Image" /></td>
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<tr>
<td>Irregular</td>
<td><img src="irregular_45.png" alt="Image" /></td>
<td><img src="irregular_60.png" alt="Image" /></td>
<td><img src="irregular_70.png" alt="Image" /></td>
<td><img src="irregular_80.png" alt="Image" /></td>
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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(N³) time) and return the transformation that yields the lowest Root Mean Squared error.

Translation matrix
\[
\begin{bmatrix}
1 & 0 & 0 & dx \\
0 & 1 & 0 & dy \\
0 & 0 & 1 & dz \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
x \\
y \\
z \\
1
\end{bmatrix}
= 
\begin{bmatrix}
x + dx \\
y + dy \\
z + dz \\
1
\end{bmatrix}
\]

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

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

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\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

Initial seeding locations

RMS Error: 1.7328
Regular 60 Degree Bevel

RMS Error: 1.7672
Irregular 90 Degree

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.

Simulated Annealing
# Timeline

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<tr>
<td>2/22 - 4/25</td>
<td>Registration and Segmentation Development</td>
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<tr>
<td>3/14 - 5/02</td>
<td>Accuracy Testing</td>
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<tr>
<td>4/25 - 5/9</td>
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Chart

February | March | April | May
---|---|---|---
1 | 8 | 15 | 22 | 29 | 7 | 14 | 21 | 28 | 4 | 11 | 18 | 25 | 2 | 9

**Testing Data Production and Planning**
- Dissect 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

February | March | April | May
---|---|---|---
1 | 14 | 4 | 11 | 2
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22 | | | | |
29 | | | | |
7 | | | | |

**Testing Data Production and Planning**
- Dissect previous work's code
- Process simple test data
- Create test defects in Solidworks or Blender
- 3D Print Skull with defect
- Create simulated skull defects

**Registration and Segmentation Development**
- Configure iPad and Structure Sensor
- Segmentation with robust geometrics
- 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 URS Integration**
- Complete modules for scanner communication
- Streamline test procedure in mock operation
- Convert mesh to coordinate codes
Readings


Questions?