Extrapolation of Missing Craniofacial Skeletal Structure via Statistical Shape Models

Project #1 Seminar Presentation
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Project Overview

• **Project Goal:** Design and implement a method for extrapolating missing anatomical craniofacial skeletal structure with the use of a statistical shape model of the human cranium.

Courtesy of Dr. Chad Gordon

Courtesy of Dr. Otake
Today’s Papers


Motivation

- We expect that the atlas based extrapolation proposed by Chintalapani, will have some discontinuities
Benazzi, et al. Introduction

• Comparing 3-Dimensional Virtual Methods for Reconstruction in Craniomaxillofacial Surgery
  – Describes 3 methods for reconstructing missing anatomy as a result of a virtual osteotomy for 15 different virtual patients
Benazzi, et al. Data Overview

- **15 CT scans of “dry” human skulls**
  - 9 Male, 6 Female
  - Varying ages (18y-47y)
  - Varying origins (10 European, 2 Australia, 2 Asia, 1 Africa)

<table>
<thead>
<tr>
<th>Label</th>
<th>Gender</th>
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<th>Origin</th>
<th>CT System</th>
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<td>Female</td>
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<td>Europe</td>
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<td>H11</td>
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<td>GE Light Speed 16</td>
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<td>H12</td>
<td>Female</td>
<td>30</td>
<td>Europe</td>
<td>GE Light Speed 16</td>
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<td>H13</td>
<td>Female</td>
<td>43</td>
<td>Europe</td>
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<tr>
<td>H14</td>
<td>Male</td>
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<td>H15</td>
<td>Male</td>
<td>18</td>
<td>Europe</td>
<td>Brilliance CT 40-Slice by Philips</td>
</tr>
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</table>

Virtual osteotomies of the left zygomatic bone performed on each skull

- 3 cutting planes through:
  - Zygomomaxillary suture
  - Frontozygomatic suture
  - Temporal-zygomatic suture
• Evaluated three approaches
  – Mirroring of the unaffected hemiface
  – Mirroring & Rigid Registration
  – Mirroring & Thin Plate Spline (TPS) warping
• Measure the surface deviation of reconstruction from ground truth
Benazzi, et al. Mirrored Reconstruction

- Use 8 anatomic landmarks to estimate a best-fit mid-sagittal plane
- Reflect the appropriate region about the plane to fill in the missing region
Benazzi, et al. Mirrored Reconstruction Results


• Perform ICP between the destination surface and the mirrored surface

**FIGURE 7.** Skull H14, anterolateral view. Reconstruction using method 2.

**FIGURE 8.** Skull H14, basal view. Reconstruction using method 2.

**FIGURE 13.** Skull H15, anterolateral view. Reconstruction using method 2.

**FIGURE 14.** Skull H15, basal view. Reconstruction using method 2.
• Identify anatomical landmarks, semi-landmarks, and curves on the mirror surface and incomplete surface
• Project the template landmarks, semi-landmarks, and curves from the mirror surface onto the incomplete surface
  – Allowing “relaxation” of the semi-landmarks and curves
• Warp the mirror template to the incomplete surface using TPS interpolation
Benazzi, et al. Mirrored and TPS Warp Reconstruction Results

**FIGURE 9.** Skull H14, anterolateral view. Reconstruction using method 3.

**FIGURE 10.** Skull H14, basal view. Reconstruction using method 3.

**FIGURE 11.** Skull H15, anterolateral view. Reconstruction using method 3.

**FIGURE 12.** Skull H15, basal view. Reconstruction using method 3.
Benazzi, et al. Results Comparison Skull H14

**FIGURE 6.** Skull H14, basal view. Reconstruction using method 1.

**FIGURE 8.** Skull H14, basal view. Reconstruction using method 2.

**FIGURE 10.** Skull H14, basal view. Reconstruction using method 3.

Nevertheless, the overall result improved, and the deviation (1.0 to 1.5 mm) of the zygomatic bone (4 mm backward from the original bone, and the frontal plane of the major contributions provided by the TPS-based mirror or mirror-registered tool. This certainly resulted from the larger amount of total reconstructed bone and the original bone was generally reduced by more precisely, the degree of interindividual variation in the contact area between the reconstruction and the original decreased when method 2 was used (Table 4, Figs 11, 12).

The best outcome was clearly provided using method 3. Color map illustrating distance between reconstruction and original model (in millimeters). Nevertheless, the results did not significantly differ when the reconstructed bone and the original cranium was achieved. This was one of the major contributions provided by the TPS-based mirror or mirror-registered tool. Esthetics, in contrast, is somewhat associated with symmetry. We are aware that the human craniofacial anatomy is characterized by a certain degree of asymmetry (both skeletal and soft tissue).

In conclusion, the alignment and regarding the general principle followed by surgeons, restoration of a symmetric shape could improve the outward appearance and hence provide better functional and aesthetic results. 3D Virtual Methods for Craniomaxillofacial Reconstruction. J Oral Maxillofac Surg 2011.


Function and esthetic restoration are the basic purposes.

In general, we have verified that the mirroring tool failed to provide a reliable solution for reconstruction, mainly when the individual face is reconstructed, mainly when the individual face is

Even if the incorrect outcome of the mirroring procedure could be improved by performing a preliminary computation; thus, the more reliable outcome depends on the assumption, because it is possible to improve the outward appearance and hence provide a remarkable contribution to the quality of life. It is

As mentioned, the degree of interindividual variation could be a valid method to determine which approach could provide the best outcome. Even if the

The best outcome was clearly provided using method 3.


Skull H14 is a typical example of low individual variation of the total individual facial asymmetry, in which the unaffected hemiface could improve the outward appearance and hence provide the best outcome. Even if the


The approach using TPS interpolation functions was among those used in paleoanthropology for fossil reconstruction, mainly when the individual face is


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Benazzi, et al. Results Summary

- Rigid registration and TPS methods out performed mirroring significantly.
- TPS had the smallest standard deviation of surface deviations from ground truth.
- Rigid registration and TPS not statistically different
  - Mann-Whitney U test

### Table 4. INDIVIDUAL ASYMMETRY,* MEAN,† AND STANDARD DEVIATION OF RECONSTRUCTIONS COMPARED WITH ORIGINAL LEFT ZYGOMATIC BONE‡

<table>
<thead>
<tr>
<th>List of Skulls</th>
<th>Total Asymmetry</th>
<th>Mirror</th>
<th>Mean</th>
<th>SD</th>
<th>Mirror Registered</th>
<th>Mean</th>
<th>SD</th>
<th>TPS Warping</th>
<th>Mean</th>
<th>SD</th>
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<td>H1</td>
<td>0.00432</td>
<td>-0.497</td>
<td>0.903</td>
<td></td>
<td>-0.032</td>
<td>0.482</td>
<td></td>
<td>-0.142</td>
<td>0.453</td>
<td></td>
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<tr>
<td>H2</td>
<td>0.00837</td>
<td>-0.557</td>
<td>1.411</td>
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<td>0.101</td>
<td>0.902</td>
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<td>-0.385</td>
<td>0.429</td>
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<tr>
<td>H3</td>
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<td>0.317</td>
<td>1.105</td>
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<td>0.166</td>
<td>0.535</td>
<td></td>
<td>-0.679</td>
<td>0.514</td>
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<tr>
<td>H4</td>
<td>0.00619</td>
<td>-0.249</td>
<td>1.204</td>
<td></td>
<td>-0.047</td>
<td>0.502</td>
<td></td>
<td>0.387</td>
<td>0.402</td>
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<tr>
<td>H5</td>
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<td>-0.186</td>
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<td>-0.108</td>
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<tr>
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<td>0.142</td>
<td>0.767</td>
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<td>0.481</td>
<td>0.499</td>
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<tr>
<td>H8</td>
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<td>0.605</td>
<td>0.836</td>
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<td>0.072</td>
<td>0.622</td>
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<td>1.551</td>
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<td>0.254</td>
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<td>H11</td>
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<td>0.352</td>
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<tr>
<td>H12</td>
<td>0.00467</td>
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<td>-0.268</td>
<td>0.633</td>
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<td>0.034</td>
<td>0.387</td>
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<tr>
<td>H13</td>
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<td>-0.772</td>
<td>0.718</td>
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<td>-0.089</td>
<td>0.361</td>
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<td>-0.041</td>
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<td>H14</td>
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<td>0.843</td>
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<td>-0.044</td>
<td>0.579</td>
<td></td>
<td>-0.280</td>
<td>0.746</td>
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<tr>
<td>H15</td>
<td>0.00746</td>
<td>-1.458</td>
<td>2.085</td>
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<td>-0.715</td>
<td>0.993</td>
<td></td>
<td>-0.295</td>
<td>0.627</td>
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</table>
The rigid registration method proposed is analogous to using the atlas based extrapolation proposed by Chintalapani.

After performing atlas-to-patient registration, we can use the TPS warping procedure to “smoothly” incorporate the missing anatomy from the atlas.

Will require the manual identification of anatomical landmarks, semi-landmarks, and curves on the patient and registered atlas instance.

Edgewarp 3D: Free software provided by Bookstein, et al. implements this.
Kazhdan, et al. Introduction

- Poisson Surface Reconstruction
- Surface reconstruction from oriented points
  - Noisy sensor data from multiple scans
  - Global solution
- Implicit function approach

![Figure 1: Intuitive illustration of Poisson reconstruction in 2D.](image)
Kazhdan, et al. Some Math

- General idea is to super-sample the oriented points into a vector field

\[ \sum_{s \in S} |P_s| \tilde{F}_{s,p}(q) \ s\tilde{\n} \equiv \tilde{V}(q). \]

  - Sample Points
  - Size of Surface Partition
  - Smoothing Filter
  - Sample Point Normal
  - Vector Field Coordinate

- Find the best fit indicator function, such that its gradient is equal to the vector field

\[ \nabla \tilde{\chi} = \tilde{V} \]

Divergence Operator

\[ \Delta \tilde{\chi} = \nabla \cdot \tilde{V} \]

Poisson Equation

Source: Kazhdan, et al. Poisson Surface Reconstruction
Kazhdan, et al. Some Math/Implementation Details

- Create an Octree of depth $D$
  - Every sample point falls into a leaf node
- Each node has a “node function”
  
  $$F_o(q) \equiv F \left( \frac{q - o.c}{o.w} \right) \frac{1}{o.w^3}.$$  

- Base function is a compactly supported approximation of a Gaussian
  
  $$F(x, y, z) \equiv (B(x)B(y)B(z))^n$$  

- Compute the vector field
  
  $$\tilde{V}(q) \equiv \sum_{s \in S} \sum_{o \in \text{Ngbr}_D(s)} \alpha_{o,s} F_o(q)s \cdot \tilde{N}$$
Kazhdan, et al. Some Math/Implementation Details

- For each octree node, define an element of the vector $v$ as:
  $$v_o = \langle \nabla \cdot \vec{V}, F_o \rangle$$

- For each pair of octree nodes, define an element of the matrix $L$ as:
  $$L_{o,o'} \equiv \langle \frac{\partial^2 F_o}{\partial x^2}, F_{o'} \rangle + \langle \frac{\partial^2 F_o}{\partial y^2}, F_{o'} \rangle + \langle \frac{\partial^2 F_o}{\partial z^2}, F_{o'} \rangle$$

  - $L$ is sparse and symmetric

- Solve the following least-squares problem:
  $$\min_{x \in \mathbb{R}^{|\Theta|}} \|Lx - v\|^2$$

- Compute the indicator function as:
  $$\tilde{\chi} = \sum_{o} x_o F_o$$
Kazhdan, et al. Results, Dragon

Figure 3: Reconstructions of the dragon model at octree depths 6 (top), 8 (middle), and 10 (bottom).

Source: Kazhdan, et al. Poisson Surface Reconstruction
Figure 6: Reconstructions of the “Happy Buddha” model using VRIP (left) and Poisson reconstruction (right).

Limitation of our approach

A limitation of our method is that it does not incorporate information associated with the acquisition modality. Figure 6 shows an example of this in the reconstruction at the base of the Buddha. Since there are no samples between the two feet, our method (right) connects the two regions. In contrast, the ability to use secondary information such as line of sight allows VRIP (left) to perform the space carving necessary to disconnect the two feet, resulting in a more accurate reconstruction.

5.3. Performance and Scalability

Table 1 summarizes the temporal and spatial efficiency of our algorithm on the “dragon” model, and indicates that the memory and time requirements of our algorithm are roughly quadratic in the resolution. Thus, as we increase the octree depth by one, we find that the running time, the memory overhead, and the number of output triangles increases roughly by a factor of four.

<table>
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<th>Tree Depth</th>
<th>Time (s)</th>
<th>Peak Memory (MB)</th>
<th># of Tris.</th>
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<td>21,000</td>
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<td>26</td>
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<td>90,244</td>
</tr>
<tr>
<td>9</td>
<td>126</td>
<td>155</td>
<td>374,868</td>
</tr>
<tr>
<td>10</td>
<td>633</td>
<td>699</td>
<td>1,516,806</td>
</tr>
</tbody>
</table>

Table 1: The running time (in seconds), the peak memory usage (in megabytes), and the number of triangles in the reconstructed model for the different depth reconstructions of the dragon model. A kernel depth of 6 was used for density estimation.

The running time and memory performance of our method in reconstructing the Stanford Bunny at a depth of 9 is compared to the performance of related methods in Table 2. Although in this experiment, our method is neither fastest nor most memory efficient, its quadratic nature makes it scalable to higher resolution reconstructions. As an example, Figure 8 shows a reconstruction of the head of Michelangelo’s David at a depth of 11 from a set of 215,613,477 samples. The reconstruction was computed in 1.9 hours and 5.2GB of RAM, generating a 16,328,329 triangle model. Trying to compute an equivalent reconstruction with methods such as the FFT approach would require constructing two voxel grids at a resolution of $2048^3$ and would require in excess of 100GB of memory.
A limitation of our method shows an example of this. In contrast, our method (c), which adapts both the scale and approach (b), introduces high-frequency noise in these regions. Figure 7: Reconstruction of samples from the region around the left eye of the David model (a), using the fixed-resolution Fourier FFT approach (b), and Poisson reconstruction (c). Figure 6: Kazhdan, et al. Results, “Happy Bhudda”
Kazhdan, et al. Results, Michelangelo’s David

Figure 8: Several images of the reconstruction of the head of Michelangelo’s David, obtained running our algorithm with a maximum tree depth of 11. The ability to reconstruct the head at such a high resolution allows us to make out the fine features in the model such as the inset iris, the drill marks in the hair, the chip on the eyelid, and the creases around the nose and mouth.

<table>
<thead>
<tr>
<th>Method</th>
<th>Time</th>
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<th># of Tris.</th>
</tr>
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<tr>
<td>Power Crust</td>
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<tr>
<td>Robust Cocone</td>
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<td>Hoppe et al 1992</td>
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<tr>
<td>Poisson</td>
<td>263</td>
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<td>911,390</td>
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</tbody>
</table>

Table 2: The running time (in seconds), the peak memory usage (in megabytes), and the number of triangles in the reconstructed surface of the Stanford Bunny generated by the different methods.

6. Conclusion
We have shown that surface reconstruction can be expressed as a Poisson problem, which seeks the indicator function that best agrees with a set of noisy, non-uniform observations, and we have demonstrated that this approach can robustly recover fine detail from noisy real-world scans.

There are several avenues for future work:
• Extend the approach to exploit sample confidence values.
• Incorporate line-of-sight information from the scanning process into the solution process.
• Extend the system to allow out-of-core processing for huge datasets.

Acknowledgements
The authors would like to express their thanks to the Stanford 3D Scanning Repository for their generosity in distributing their 3D models. The authors would also like to express particular gratitude to Szymon Rusinkiewicz and Benedict Brown for sharing valuable experiences and ideas, and for providing non-rigid body aligned David data.

References

© The Eurographics Association 2006.
Kazhdan, et al. Application to Our Project

- Perform atlas-to-patient registration
- For each vertex, in the “known” patient and “estimated” atlas instance, compute the inward surface normal
  - Treat these as oriented points
• Mask out the estimated points that fall within the “known” region
• Run Poisson Surface Reconstruction
  — software available on M. Kazhdan’s web site
Questions?
“Sliding” Semi-landmarks

Figure 4 – Landmarks (red), curve semilandmarks (orange), and surface semilandmarks (blue) on a modern human cranium. A: Semilandmarks are allowed to slide along tangents (curves), and tangent planes (surfaces) so as to minimize the thin-plate spline bending energy between this specimen and the Procrustes average shape of the sample. B: After sliding, the semilandmarks are projected back onto the surface. Arrows connect semilandmarks before and after sliding. In this example, the positions of the semilandmarks change only subtly.