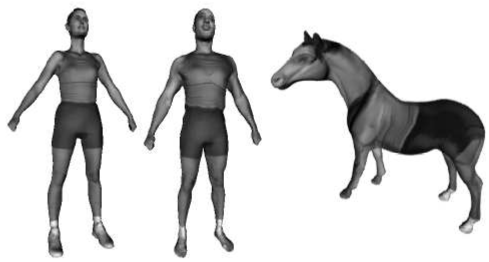
Registration of Deformable Objects



Christopher DeCoro

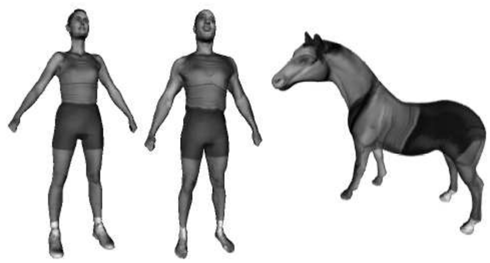
__Includes content from:__
Consistent Mesh Parameterizations, Praun et. al, Siggraph 2001
The Space of Human Body Shapes, Allen et. al, Siggraph 2003
Shape-based 3D Surface Correspondence Using Geodesics and Local Geometry, Wang et al, CVPR 2000

Talk outline

- Introduction
  - Definition
  - Motivation
- Consistent Mesh Parameterization
- Parameterization of Human Body Shapes
- Surface Correspondence Using Geodesics and Local Geometry
- Conclusion

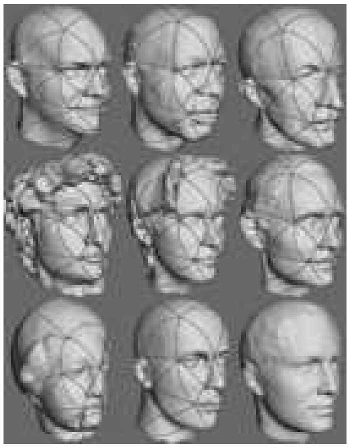
Definition

- What is Deformable Body Registration?
- Establishing 1 to 1 mapping between points on one model, and corresponding points on a similar, but deformed, model
- Example: Texture Transfer
  - The male human, female human, and horse models have parts in correspondence, and texture coords can be shared

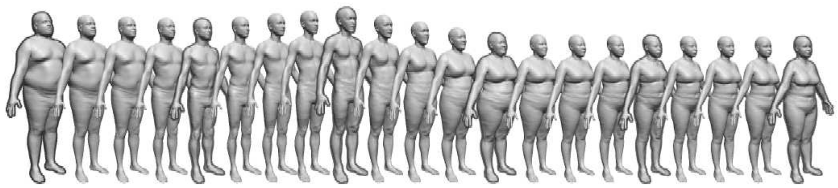


Motivation – Digital Geometry Processing

- Surface do not have simple parameterization, as do images
  - Images are in Euclidean space
  - Images are regularly sampled
  - Mesh Surfaces are neither
- Registration provides consistent parameterization
  - Allows for basic operations like mean
  - More complex signal processing



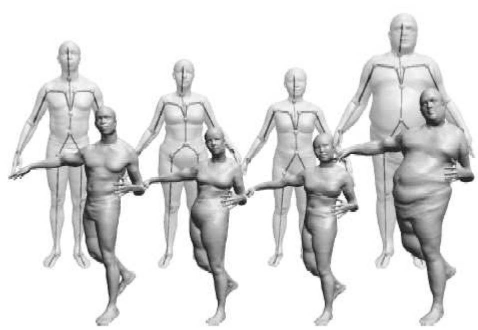
Motivation - Morphing



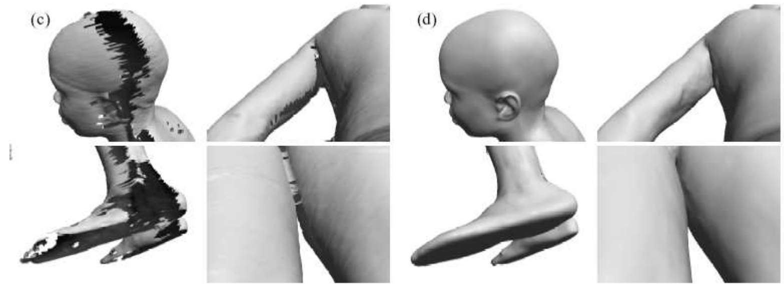
- Would like to smoothly transition from one model to another
- When registered, simply use linear combinations of vertices

Motivation – Attribute Transfer

- Copy surface attributes from one surface to another
  - Texture transfer (as shown previously)
  - Deformation weight transfer (below)
  - Segmentation transfer



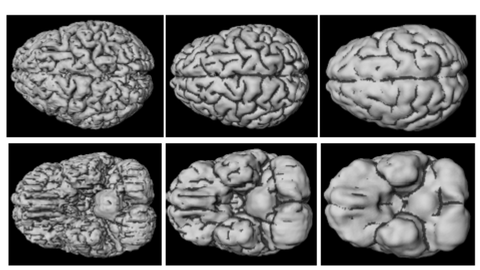
Motivation – Correct Hole Filling



- Models captured through range scanning have holes
- Smooth hole filling produces artifacts in flat regions
  - Such as the soles of the feet
- Reparameterization allows for correct behavior

Motivation – Medical Analysis

- Would like to identify common features
  - Most organs do not differ greatly from person to person
  - In brains, we see homothetic deformation (local uniform stretch)
- Can use domain-specific knowledge to guide registration

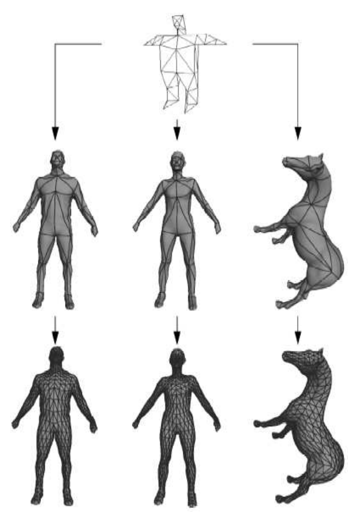


Talk outline

- Introduction
- Consistent Mesh Parameterization
  - Purpose and Problem Specification
  - Topologically Equivalent Nets
  - Restricted Brush Fire Algorithm
  - Fair Boundary Curves & Heuristics
- Parameterization of Human Body Shapes
- Surface Correspondence Using Geodesics and Local Geometry
- Conclusion

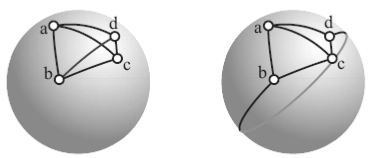
Purpose and Problem Specification

- Algorithm Input
  - Set of meshes S
  - Feature points F defined on each mesh M
- Algorithm Goal
  - Determine common base domain B and connectivity L_0
  - Remesh each M with base domain B
  - Create fair patch boundaries equivalent to L_0



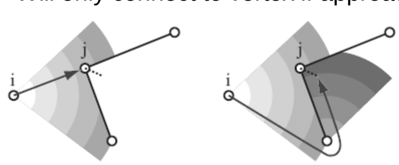
Topologically Equivalent Nets

- Definition: A **patch** is a region of semi-regular connectivity in which triangles correspond to a single triangle in B
- Definition: A **net** is the outline of patch boundaries
- We want a net that matches the connectivity L0
  - Two patch boundaries may only intersect at a feature vertex
  - Each feature vertex has a consistent cyclical ordering of edges
  - Patch boundaries may not intersect
- Naïve algorithm (shortest path) does not achieve this

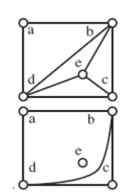


Restricted Brush Fire Algorithm

- Standard Brush Fire
  - Starts fire at vertex
  - Fire expands uniformly until it hits other vertex
  - That is the shortest path
- Restricted Brush Fire
  - Uses existing paths as firewalls
  - Will only connect to vertex if approached from correct ordering

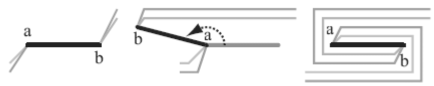


  - Must avoid blocking off vertices
  - Avoid completing any cycle until spanning tree of L0 traced



Fair Boundary Curves

- Rather than simply accept topologically equivalent net, we would like certain properties
  - Equal distribution of surface area between patches
  - Smooth Patch Boundaries
  - Fair patch boundaries (should not swirl)



- First two can be handled using relaxation
  - Iterative technique that involves progressively improving curve
- Third requires optimization of complicated expression
  - Intractable, so try heuristics

Fair Boundary Curve Heuristics

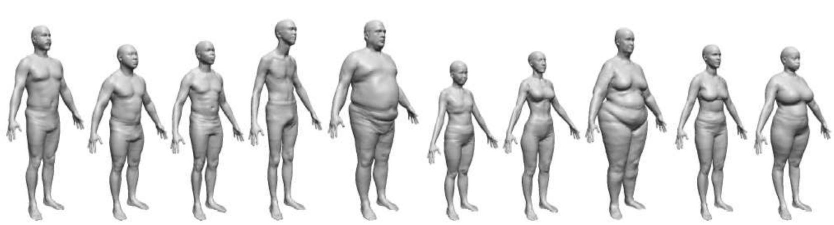
- Parameterization
  - Construct parameterization from base mesh to target
- Tracing Curves
  - Construct objective function that makes curves repel each other
- Priority Queues
  - Use a priority queue to control validity testing
- Swirl Detection
  - Trace a line to detect swirl crossings
- Curve Straightening
  - Allow curves to pass through center of triangles

Talk outline

- Introduction
- Consistent Mesh Parameterization
- Parameterization of Human Body Shapes
  - Problem Specification
  - Optimization Variables
  - Objective Function
  - Algorithm Procedure
  - Feature Analysis
  - Markerless Matching
- Surface Correspondence Using Geodesics and Local Geometry
- Conclusion

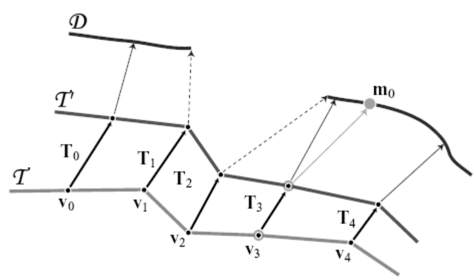
Problem Specification

- Algorithm Input
  - Set of human range images
    - All in similar poses
  - Set of colored feature markers
- Algorithm Goal
  - Develop correspondence from template to target
  - Compute affine transform for each vertex
  - Minimize error function



Optimization Variables

- Algorithm viewed as optimization problem
  - Given an initial template surface with vertices v_i
  - Corresponding affine transformation matrices T_i
  - Current state is T_i v_i for all i (see diagram)
  - Find values of T_i to minimize objective function
  - Attempts to find a “good fit” (blue) of template (cyan) to target (red)



Objective Function

- Objective Function has three weighted terms
  - Data error
  - Smoothness error
  - Marker error

$$E = \alpha E_d + \beta E_s + \gamma E_m$$

- Will use different weights in each phase of process
  - Multistep / Multi-resolution fitting process

Objective Function – Data Error

- Data Error term requires current match to be close to target
  - Uses distance from each transformed vertex to the target surface
  - Weighted by confidence measure (from scanning)
  - Hole regions have weight = 0
  - Sums total error

$$E_d = \sum_{i=1}^{n} w_i \,\mathrm{dist}^2(\mathbf{T}_i \mathbf{v}_i, \mathcal{D})$$

- Distance function
  - Uses transformed template vertex
  - Takes minimum distance to “compatible” vertices in target
  - Compatible defined as those with normal w/in 90 deg.

Objective Function – Smoothness Error

- Measures smoothness of deformation applied to template
  - Problem is under-constrained using data error
  - E_s measures change in T_I between adjacent vertices
  - Encourages similarly-shaped features to be mapped to each other

$$E_s = \sum_{\{i,j \mid \{\mathbf{v}_i, \mathbf{v}_j\} \in edges(\mathcal{T})\}} \|\mathbf{T}_i - \mathbf{T}_j\|_F^2$$

  - Uses Frobenius norm (vector L2 norm)

Objective Function – Marker Error

- Data and Smoothness Error can hit local minima
  - Example: left arm transformed to right arm
- Solution: Use pre-labeled markers on the test subjects
  - Viewed as white dots in the range image
  - Correspondences set up beforehand (as in Consistent Mesh Parameterization)
  - 74 markers per subject (not all are used, however)
- Measure distance from template marker to target marker
  - K_I are the indices of the markers in template, m_I are target markers

$$E_m = \sum_{i=1}^{m} ||\mathbf{T}_{\kappa_i}\mathbf{v}_{\kappa_i} - \mathbf{m}_i||^2$$

Algorithm Procedure

- Minimize error function using L-BFGS-B algorithm
  - Quasi-Newton method with limited memory usage

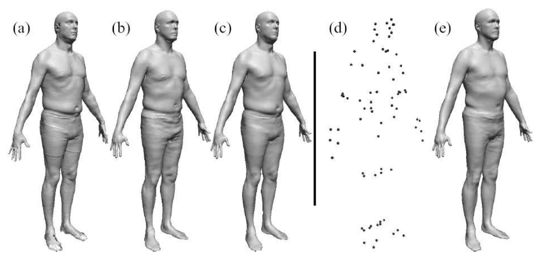
$$E = \alpha E_d + \beta E_s + \gamma E_m$$

- Make four passes over data (2 low res, 2 high res)
  - Fit markers (low res, $\alpha = 0$, $\beta = 1$, $\gamma = 10$)
  - Refit using data term (low res, $\alpha = 1$, $\beta = 1$, $\gamma = 10$)
  - Repeat in high resolution (hi res, $\alpha = 1$, $\beta = 1$, $\gamma = 10$)
  - Refit using predominantly data term (hi res, $\alpha = 10$, $\beta = 1$, $\gamma = 1$)

Markerless / Marker-only Matching

- Using PCA, we can remove the marker requirement
  - A set of training data is fit using markers
  - Other data can be registered using unmarked range scans
  - Uses PCA weights to search PCA space, not transformation space

- Also, we can use PCA to remove the range images
  - Only use markers; can be captured with much cheaper equipment
  - Allows us to determine approximate shape of object

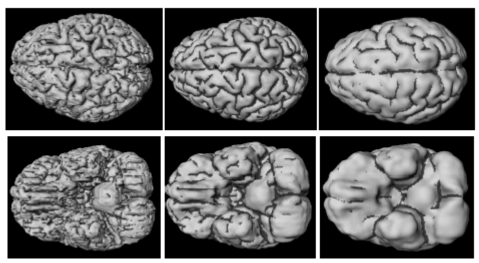


Talk outline

- Introduction
- Consistent Mesh Parameterization
- Parameterization of Human Body Shapes
- Surface Correspondence Using Geodesics and Local Geometry
  - Problem Specification
  - Objective Function
  - Feature Match Measure
  - Correspondence Interpolation
- Conclusion

Problem Specification

- Algorithm Input
  - Set of human brain volumes (triangulated w/ Marching Cubes)
  - Prelabeled reference brain mesh (low resolution)
- Algorithm Goal
  - Develop correspondence from template to target (as before)
  - Identify particular features in the brain (gyri, sulci)
  - Minimize error function



Objective Function

- Minimizes error between vertex and feature point

$$O_{ij} = d_{ij} \cdot n_{ij} \cdot f_{ij}$$

- Euclidean distance measure

$$d_{ij} = 1 + \sqrt{[x_i - x_j]^2 + [y_i - y_j]^2 + [z_i - z_j]^2}$$

- Surface Normal Match

$$n_{ij} = 2 - \vec{n}_i \cdot \vec{n}_j$$

Feature Match Measure

- Domain-specific measurement based on brain features
- Determined by measuring curvature
  - Compute Mean curvature and Gaussian curvature

$$K = \frac{\sum_{(i,j,k)\in\Omega} \left[\begin{array}{c} L_i^2(L_{jj}L_{kk} - L_{jk}^2) \\ +2L_iL_j(L_{ik}L_{jk} - L_{ij}L_{kk}) \end{array} \right]}{(L_i^2 + L_j^2 + L_k^2)^2}$$

$$H = \frac{\sum_{(i,j,k)\in\Omega} \left[(L_{ii} + L_{jj})L_k^2 - 2L_iL_jL_{ij}\right]}{2(L_i^2 + L_j^2 + L_k^2)^{3/2}}$$

  - Compute principle curvatures k1 = H + sqrt(H^2 – K); k2 = H – sqrt(H^2-K)
  - Compute Shape Index Function S = 2/PI * arctan[(k2 + k1) / (k2 – k1)]
  - Compute Signed Curvedness

$$C_s = \begin{cases} \sqrt{\frac{k_1^2+k_2^2}{2}}, & \text{if } S \geq 0 \\ -\sqrt{\frac{k_1^2+k_2^2}{2}}, & \text{if } S < 0 \end{cases}$$

  - Halfway there!

Feature Match Measure (2)

- We now use curvedness to estimate feature type
  - Gyrus is a ridge in the brain
  - Sulcus is a crease in the brain

$$t = \begin{cases} \text{gyrus}, & \text{if } C_s > K_g \\ \text{sulcus}, & \text{if } C_s < -K_s \\ \text{no feature}, & \text{otherwise} \end{cases}$$

  - Adjust the Kg and Ks to get a certain percentage of feature points
  - Use labeling of points in template brain to compute scale

$$scale = \begin{cases} 1, & \text{if } l = 3 \text{ or } 4 \\ 2, & \text{if } l = 1 \\ 3, & \text{if } l = 2 \end{cases}$$

  - Type 1 = interhemispheric fissure sulcal points; Type 2 = brain stem crease
  - Type 3 = other sulcal points; Type 4 = gyral points
  - Almost there!

Feature Match Measure (3)

- Finally, we use all this information to compute feature measure

$$f_{ij} = \begin{cases} 1.0, & \text{if } (t_i, t_j) = \begin{cases} \text{(sulcus, sulcus)} \\ \text{(gyrus, gyrus)} \\ \text{(no feature, no feature)} \end{cases} \\ 2.8, & \text{if } (t_i, t_j) = \begin{cases} \text{(sulcus, no feature)} \\ \text{(gyrus, no feature)} \end{cases} \\ 3.0, & \text{if } (t_i, t_j) = \text{(sulcus, gyrus)} \end{cases}$$

- Assign correspondence to point that minimizes error func.
  - In this paper, perform exhaustive search in 15-voxel radius

Correspondence Interpolation

- Given mapping to feature points, map intermediate points
  - Same idea as in Consistent Mesh Parameterization
- Trace geodesic path
  - Between vertices that are connected in template mesh
  - Use Fast Marching Method for finding curves
- Subdivide patches
  - Insert additional vertices at midpoints of geodesic paths
  - This produces higher resolution mesh
  - Template mesh begins to approximate target mesh
- Repeat
  - Process is repeated to iterative improve correspondence
  - Example given of 4 iterations

Conclusion

- Progress needs to be made in initializing registration
  - All require correspondences to be initially pre-selected
  - One can use PCA to avoid features after training
  - Future work might use local shape descriptors
    - » Would have to be robust against misplaced feature points
  - This would allow for use in search and retrieval

- Results with initial features are quite good
  - Allows for wide variety of applications

- Related Project Ideas
  - Monkey Skulls – Create correspondence
  - Brain registration using distance over surface