Iterative Closest Point Algorithm for Rigid Registration of Ear Impressions

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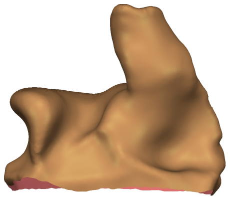
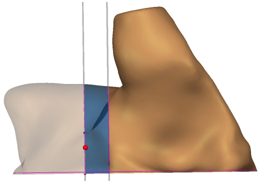
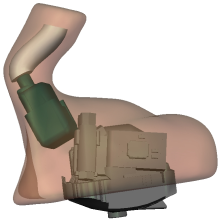
Outline

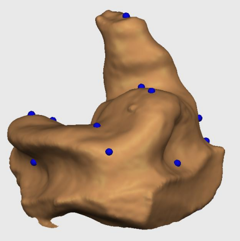
Motivation and Background

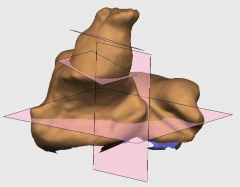
- Automatic design of customized in-the-ear hearing aids

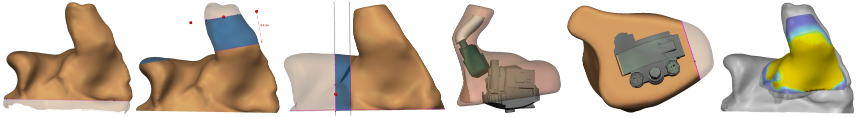






Motivation and Background

- Automation framework based on an expert system and anatomical features
  - Integrated into CAD software
  - *Feature detection performance crucial for design quality*

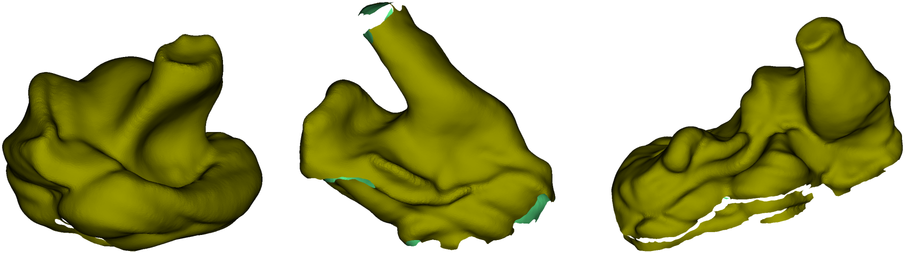






Motivation and Background

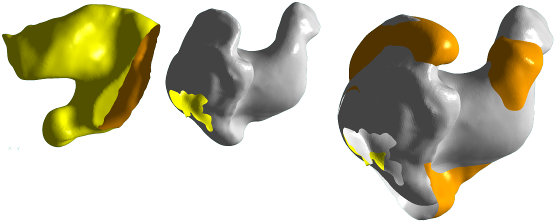
- Currently surface-analyzing algorithms employed (peaks, concavities, ridges)
  - Good results on average
  - Unstable or total failure in case of bad or unusual ear impressions



Motivation and Background

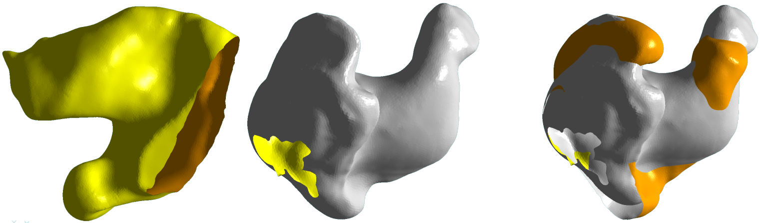
Labeled set $\mathcal{S}_{\text{rep}}$ — Alignment — Feature transformation

$$S_1, \ \ldots, \ S_N \rightarrow S_{\text{new}} \xrightarrow{\mathbf{T}_i,\, F_i} F_{\text{new}} = \mathbf{T}_i \cdot F_i$$



Motivation and Background

- Requirements
  - *Robust and accurate ear impression alignment*
  - Feature projection / transformation



The Iterative Closest Point (ICP) Algorithm

- Iterative algorithm to minimize differences between two or more point clouds

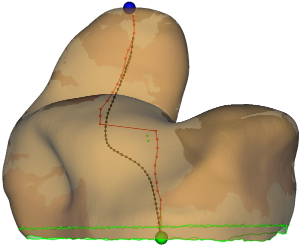
1. Point matching (associate $\mathbf{p}_i \in P$ with $\mathbf{q}_i \in Q$)
2. Estimate transformation $\mathbf{T} \leftarrow \arg\min_{\mathbf{T}} \sum_{i=1}^{N} \omega_i \left\| \mathbf{T} \cdot \mathbf{p}_i - \mathbf{q}_i \right\|^2$
3. Transform point cloud $P' = \mathbf{T} \cdot P$
4. Iterate

ICP for Ear Impressions

1. Rough alignment – Centerline alignment
   - Reduced representation – centerline
   - Point-to-point error metric
     - Closed form solution available, based on SVD
     - Robust and easy to implement
2. Final alignment
   - Sub-sampled representation
   - Point pair rejection and weighting
   - Point-to-plane error metric
     - No closed form solution available, but can be linearized if rough alignment available
     - Very accurate in case smooth or planar areas have to be aligned

Centerline Alignment

- Centerline representation of ear impression $L = (\mathbf{l}_1, \ldots, \mathbf{l}_N)$
- Initial centerline computed by slicing ear impression parallel to bottom opening
- Centerline refinement using internal and external energies



$$E_{\text{ext},i} = \frac{1}{N_v} \sum_{v=1}^{N_v} \frac{\mathbf{x}_{v,i}}{|\mathbf{x}_{v,i}|_1},$$

$$E_{\text{int},i} = \mathbf{l}_{i-1} + \mathbf{l}_{i+1} - 2\mathbf{l}_i$$

$\mathbf{x}_{v,i}$ = random ray intersection point

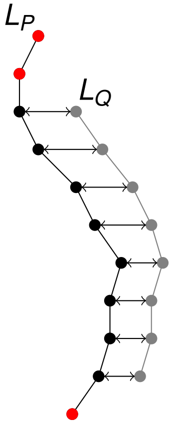
N_v = number of rays

α, β = *weights*

- Update rule: $\mathbf{l}'_i = \mathbf{l}_i + \alpha E_{\text{int},i} + \beta E_{\text{ext},i}$

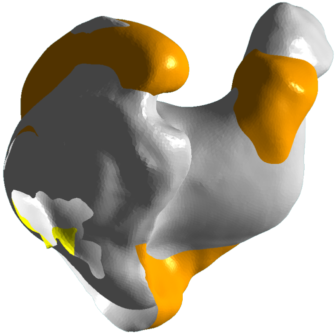
Centerline Alignment

- Point matching:
  - Centerlines are ordered from top to bottom
  - Iteratively shift centerlines along each other
  - Point matching by centerline indexes i
  - Very fast but rough alignment
  - Result: $\mathcal{T} = \{\mathbf{T}_1, \ldots, \mathbf{T}_N\}$



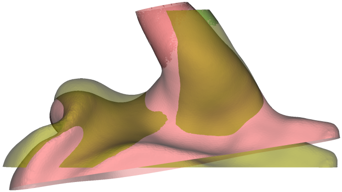
Final Alignment

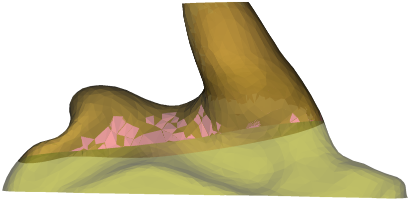
- Point matching:
  - Sub-sampling of mesh resulting in 1000 vertices (25k original)
  - Grid structure similar to an octree
- Properties:
  - Usage of initial alignment
  - Point-to-plane error metric
  - Application of point pair rejection techniques
  - Application of point pair weighting techniques

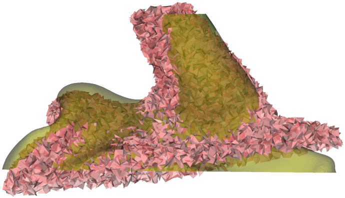


Experiments, Data

- Experimental setup
  - 400 ear impressions $\mathcal{S}$ – two copies $\mathcal{S}_{\text{cut}}$, $\mathcal{S}_{\text{rot}}$
  - $\mathcal{S}_{\text{cut}}$: cutting of each sample (25% loss)
  - $\mathcal{S}_{\text{rot}}$ rotation (10°) and random noise
  - Alignment of $\mathcal{S}_{\text{cut}}$ and $\mathcal{S}_{\text{rot}}$
  - $\mathcal{S}$ used for error computation







Evaluation – Point Selection

- Sub-sampling of meshes, resulting in 1000 vertices
  - uniform
  - random

point selection	average error	average time	average # pairs[1]
full	0.0244223	25.8 sec	13182.1
random	0.0477856	1.6 sec	748.2
uniform	0.0657007	1.7 sec	719.4

[1] Meshes do not overlap, therefore less than 1000 point pairs available.

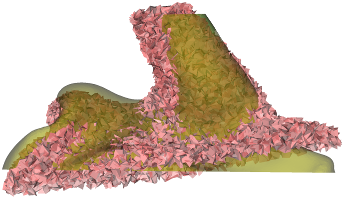
Evaluation – Point Pair Rejection

- Point pair rejection techniques
  - Single or double threshold (2 iterations)
  - Worst pairs: reject the worst 10% based on point pair distance
  - Standard deviation: reject all pairs exceeding 2.5σ (σ – standard deviation of point pair distance)

rejection	average error	average time	average # pairs
no rejection	1.10885	1.8 sec	1000
one threshold	0.0800223	1.1 sec	814.6
two thresholds	0.0477603	1.7 sec	749.1
worst pairs	0.0488082	1.2 sec	732.9
standard deviation	0.0490695	1.1 sec	748.7

Evaluation – Point Pair Weighting

- Objective function:
  $\mathbf{T} \leftarrow \arg\min_{\mathbf{T}} \sum_{i=1}^{N} \omega_i \left\|\mathbf{T} \cdot \mathbf{p}_i - \mathbf{q}_i\right\|^2$
- Point pair weighting techniques
  - Distance penalty: $\omega_i = 1 - \frac{d(\mathbf{p}_i, \mathbf{q}_i)}{d_{\max}}$
  - Normal compatibility: $\omega_i = \mathbf{n}_{p_i} \mathbf{n}_{q_i}$



weighting	average error	average error without noise
no weighting	0.0467054	0.011522
distance penalty	0.0471554	0.005563
normal compatibility	0.0502212	0.010572

Summary and Outlook

- Adapted ICP for ear impressions: robust, accurate, reasonably fast
    1. Centerline alignment using point-to-point
    2. Final alignment using point-to-plane
- Evaluation on large data set
    - Point selection: random
    - Point pair rejection is crucial, double threshold best error, but slow
    - Point pair weighting not crucial and can have negative effects
- Outlook: First results of feature projections show an improvement about 30 %

Thank you!

Thank you for your attention!