Iterative Closest Point Algorithm for Rigid Registration of Ear Impressions

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Outline

1 Motivation and Background
2 Iterative Closest Point Algorithm for Ear Impressions
3 Experiments and Results
4 Summary and Outlook
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 $S_{\text{rep}}$

Alignment

Feature transformation

$F_{\text{new}} = T_{i} \cdot F_{i}$
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 \( p_i \in P \) with \( q_i \in Q \))
2. Estimate transformation \( T \leftarrow \arg \min_T \sum_{i=1}^{N} \omega_i \| T \cdot p_i - q_i \|^2 \)
3. Transform point cloud \( P' = T \cdot P \)
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 $L = (l_1, \ldots, l_N)$
- Initial centerline computed by slicing ear impression parallel to bottom opening
- Centerline refinement using internal and external energies

\[
E_{\text{ext},i} = \frac{1}{N_v} \sum_{v=1}^{N_v} \frac{x_{v,i}}{|x_{v,i}|_1}
\]

\[
E_{\text{int},i} = l_{i-1} + l_{i+1} - 2l_i
\]

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

$x_{v,i} = \text{random ray intersection point}$

$N_v = \text{number of rays}$

$\alpha, \beta = \text{weights}$
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

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Experiments, Data

- Experimental setup
  - 400 ear impressions $S$ – two copies $S_{\text{cut}}$, $S_{\text{rot}}$
  - $S_{\text{cut}}$: cutting of each sample (25% loss)
  - $S_{\text{rot}}$: rotation ($10^\circ$) and random noise
  - Alignment of $S_{\text{cut}}$ and $S_{\text{rot}}$
  - $S$ used for error computation
## Evaluation – Point Selection

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

<table>
<thead>
<tr>
<th>point selection</th>
<th>average error</th>
<th>average time</th>
<th>average # pairs¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>full</td>
<td>0.0244223</td>
<td>25.8 sec</td>
<td>13182.1</td>
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<tr>
<td>random</td>
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<td>1.6 sec</td>
<td>748.2</td>
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<tr>
<td>uniform</td>
<td>0.0657007</td>
<td>1.7 sec</td>
<td>719.4</td>
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</tbody>
</table>

¹Meshes 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 $2.5\sigma$ ($\sigma$ – standard deviation of point pair distance)

<table>
<thead>
<tr>
<th>rejection</th>
<th>average error</th>
<th>average time</th>
<th>average # pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>no rejection</td>
<td>1.10885</td>
<td>1.8 sec</td>
<td>1000</td>
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<tr>
<td>one threshold</td>
<td>0.0800223</td>
<td>1.1 sec</td>
<td>814.6</td>
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<tr>
<td>two thresholds</td>
<td>0.0477603</td>
<td>1.7 sec</td>
<td>749.1</td>
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<tr>
<td>worst pairs</td>
<td>0.0488082</td>
<td>1.2 sec</td>
<td>732.9</td>
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<tr>
<td>standard deviation</td>
<td>0.0490695</td>
<td>1.1 sec</td>
<td>748.7</td>
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</tbody>
</table>
Evaluation – Point Pair Weighting

- Objective function:
  \[ T \leftarrow \text{arg min}_T \sum_{i=1}^{N} \omega_i \| T \cdot p_i - q_i \|^2 \]

- Point pair weighting techniques
  - Distance penalty: \( \omega_i = 1 - \frac{d(p_i, q_i)}{d_{\text{max}}} \)
  - Normal compatibility: \( \omega_i = n_{p_i} \cdot n_{q_i} \)

<table>
<thead>
<tr>
<th>weighting</th>
<th>average error</th>
<th>average error without noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>no weighting</td>
<td>0.0467054</td>
<td>0.011522</td>
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<tr>
<td>distance penalty</td>
<td>0.0471554</td>
<td>0.005563</td>
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<tr>
<td>normal compatibility</td>
<td>0.0502212</td>
<td>0.010572</td>
</tr>
</tbody>
</table>
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 for your attention!