Shape, Pose and Resolution Invariant Correspondences for Non-rigid Articulated Objects

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Motivation:
Align 3D model to laser scan data

[Allen et al. ‘03]

high-resolution scan
(~ 80000 points)

low-resolution model
(~ 5000 points)
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(~ 80000 points)

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low-resolution model
(~ 5000 points)
Challenge 1:
Local geometry changes with pose

pose variation
Challenge 2:
Local geometry changes with shape

shape variation
Challenge 3:
Correspondence between meshes with different resolution
Challenge 3:
Correspondence between meshes with different resolution

almost uniform resolution

Different resolution between scan and model
Challenge 3: Correspondence between meshes with different resolution

almost uniform resolution

Different resolution within model
Challenge 4:
Exponential space of correspondences

- approximately $N^M$ possible correspondences
Challenge 4:
Exponential space of correspondences

- approximately $3000^{4000}$ possible correspondences!

=> Search may end up in local minima
Question

“How do we search for correspondences between non-rigid articulated objects with significant variation in pose, shape and resolution?”
Previous work: Correlated Correspondence (CC) [Anguelov et al. ’04]

- Probabilistic framework
  - loose pairwise geodesic constraints
  - geometric local descriptors (spin images [Johnson 1997])
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X only for high-res scans
X small shape variation
Previous work:
Generalized Multidimensional Scaling (GMDS)
[Bronstein et al. ’06]

• Root Mean Squared (RMS) error between geodesic distances on surfaces Z, X
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X  Local minima

surface Z  surface X
Contributions

X HIGH-res to HIGH-res meshes
X small shape variation
X sensitive to local minima
Contributions

- HIGH-res to HIGH-res meshes
- Small shape variation
- Sensitive to local minima

- Strict geodesic constraints
- Pose/shape/res invariant local descriptors
Contributions

- X HIGH-res to HIGH-res meshes
- X small shape variation
- X sensitive to local minima

- ✓ HIGH-res to HIGH/LOW-res meshes
- ✓ large shape/pose variation
- ✓ more meaningful correspondences
Problem Statement

Input:

Data mesh

\[ Z = (V^Z, E^Z) \]
\[ V^Z = (z_1, \ldots, z_{Nz}) \]

Model mesh

\[ X = (V^X, E^X) \]
\[ V^X = (x_1, \ldots, x_{Nx}) \]
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Problem Statement

Input:

$$Z = (V^Z, E^Z)$$
$$V^Z = (z_1, \ldots, z_{Nz})$$

Data mesh

$$c_k = x_i$$

Model mesh

Output: correspondence variables

$$C = (c_1, \ldots, c_{Nz})$$
$$c_k \in \{1, \ldots, N^X\}$$
Conditional Random Field (CRF) model

\[
\text{arg max}_C \ p(C \mid X, Z)
\]

\[
p(C \mid X, Z) \propto \prod_k \phi(c_k, X, Z) \prod_{k,l} \psi(c_k, c_l, X, Z)
\]

geodesic signature potential

pairwise geodesic potential
Pairwise geodesic potential

\[
\psi(c_k = x_i, c_l = x_j, X, Z) = N(h(c_k = x_i, c_l = x_j; X), h(x_i, x_j; Z), \sigma_{kl}^2)
\]
Geodesic signature potential

\[ \psi(c_k = x_i, X, Z) = N(g(c_k = x_i; X); g(k; Z), \sigma_k^2) \]

only subset of geodesic paths is displayed
Our algorithm: Probabilistic Geodesic Surface Embedding (PGSE)

[Diagram showing data mesh and model mesh with correspondence points and BP algorithm flow from data mesh to model mesh for coarse and fine correspondences]
Dataset 1 – SCAPE bodies

• SCAPE model [Anguelov et al. ’05]
  – pose and shape factorization
Dataset 2 – TOSCA nonrigid world

- 148 nonrigid objects (females, males, cats, dogs, horses etc.)
- only “pose” variation

http://tosca.cs.technion.ac.il/book/resources_data.html
Results – SCAPE bodies

GMDS

data mesh

model mesh

PGSE

data mesh

model mesh
Geodesic-based error metric

\[ T_g = \text{mean} ( \text{geodesic distances in data mesh} \quad - \quad \text{corresponding geodesic distances in model mesh} ) \]

- **GMDS**
  - data mesh
  - model mesh
  - \( T_g = 0.043 \)
  - Low error
  - Bad fit

- **PGSE**
  - data mesh
  - model mesh
  - \( T_g = 0.06 \)
  - Higher error
  - Better fit
Voronoi-based error metric

$$T_e = \text{mean}\left(\text{Vorono}\text{ areas in data mesh}\right) - \text{mean}\left(\text{Vorono}\text{ areas in model mesh}\right)$$

GMDS

- $T_e = 0.28$

PGSE

- $T_e = 0.11$
Mean error on pose variation

Wilcoxon Signed Rank test

$p = 0.013$
Mean error on shape variation

$p = 3 \times 10^{-4}$
Mean error on pose and shape variation

\[ p = 3.15 \times 10^{-4} \]
Resolution experiments

mean SCAPE body:

template:
Results – TOSCA nonrigid world

GMDS

PGSE

data mesh    model mesh    data mesh    model mesh
Results – TOSCA nonrigid world

- 146 objects, various poses

<table>
<thead>
<tr>
<th></th>
<th>GMDS</th>
<th>PGSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Voronoi error</td>
<td>0.2799</td>
<td>0.1410</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.1564</td>
<td>0.1059</td>
</tr>
</tbody>
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Wilcoxon Signed Rank test

\[ p = 3 \times 10^{-16} \]
Conclusions

• Pose/shape/resolution invariant correspondence
  – geodesic distance preservation
  – local descriptors

• Future work:
  – experiments with 3D laser scans
  – partial matching
  – changes in topology (intersecting parts)
  – evaluation using ground truth correspondences
Acknowledgements

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Thank you!