3D Shape Analysis for Quantification, Classification and Retrieval

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PhD Defense

Advisor: Prof Linda Shapiro
General Motivation

• Increasing number of 3D objects available

• Want to store, index, classify and retrieve objects **automatically**

• Need 3D object descriptor that captures global and local shape characteristics
Medical Motivation

• Researchers at Seattle Children’s use CT scans and 3D surface meshes

• Investigate head shape dysmorphologies due to craniofacial disorders

• Want to represent, analyze and quantify variants from 3D head shapes
22q11.2 Deletion Syndrome (22q11.2DS)

- Caused by genetic deletion
- Cardiac anomalies, learning disabilities
- Multiple subtle physical manifestations
- Assessment is subjective
Deformational Plagiocephaly

- Flattening of head caused by pressure
- Delayed neurocognitive development
- Assessment is subjective and inconsistent
- Need **objective** and **repeatable** severity quantification method
Objective

• Investigate new methodologies for representing 3D shapes

• Representations are flexible enough to generalize from specific medical to general 3D object tasks

• Develop and test for 3D shape classification, retrieval and quantification
Outline

• Related Literature
• Datasets
• Base Framework
• 3D Shape Analysis
• Conclusion
Shape Retrieval Evaluation Contest (SHREC)

• Benchmark with common test set and queries

• **Objective**: evaluate effectiveness of 3D shape retrieval algorithms

• No descriptor performs best for all tasks
## 3D Object Descriptor

<table>
<thead>
<tr>
<th></th>
<th>Feature-based</th>
<th>Graph-based</th>
<th>View-based</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Eg</strong></td>
<td>Shape distributions</td>
<td>Skeleton</td>
<td>Light Field Descriptor</td>
</tr>
<tr>
<td><strong>+</strong></td>
<td>Compact</td>
<td>Articulated object</td>
<td>Best in SHREC</td>
</tr>
<tr>
<td><strong>-</strong></td>
<td>Not discriminative</td>
<td>Computationally expensive</td>
<td>Computationally expensive</td>
</tr>
</tbody>
</table>
Deformational Plagiocephaly Measurements

- Anthropometric landmark
  - Physical measurements using calipers

- Template matching

- Landmark photographs

Cranial Index (CI)
Oblique Cranial Length Ratio (OCLR)
22q11.2DS Measurements

• Anthropometric landmark
• 2D template landmark + PCA
  Boehringer et al.
  Gabor wavelet + PCA to analyze 10 facial dysmorphologies
  - Manual landmarks
• 3D mean landmark + PCA
  Hutton et al.
  Align to average face + PCA
Outline

• Related Literature
• Datasets
• Base Framework
• 3D Shape Analysis
• Conclusion
Datasets

- 22q11.2DS
- Deformational Plagiocephaly
- Heads

\( \rightarrow \) non similar shapes

\{ \text{similar overall shape with subtle distinctions} \)
22q11.2DS Dataset

• Dataset: 189 (53 + / 136 -), 86 (43 + / 43 -)
• Assessed by craniofacial experts
  – Selected 9 facial features that characterize disease
Deformational Plagiocephaly Dataset

- Dataset: 254 (154+/100 -), 140 (50+/90 -)
- Assessed by craniofacial experts
  - 5 different affected areas of head
Heads Dataset

• 15 original objects - 7 classes
• Randomly morph each object
SHREC Dataset

• 425 objects - 39 classes
Outline

• Related Literature
• Datasets
• Base Framework
• 3D Shape Analysis
• Conclusion
Base Framework

Input:
Surface mesh

3D Shape Analysis

Feature extraction

Curvature
Surface normal
Azimuth elevation angles

Ex: smoothed curvature

Feature aggregation

Neighborhood radius

histograms
Learning salient points

2D longitude-latitude salient map

2D azimuth elevation histogram

Learning 3D shape quantification

3D Shape Analysis
Learning salient points

2D longitude-latitude salient map

3D Shape Analysis

2D azimuth elevation histogram

Learning 3D shape quantification
Learning Salient Points

- Salient points are application dependent
- Classifier learns characteristics of salient points
Learning Salient Points

- **22q11.2DS**
  - Training on subset craniofacial landmarks

- **Deformational Plagiocephaly**
  - Training points marked on flat areas on head
Learning Salient Points – General 3D Objects

- **Training** on craniofacial landmarks on different classes of heads

- **Predicted** salient points
Learning salient points

3D Shape Analysis

2D longitude-latitude salient map

2D azimuth elevation histogram

Learning 3D shape quantification
2D Longitude-Latitude Salient Map

- Classification
- Retrieval
- Salient Views

Salient Point Pattern Projection
Salient Point Pattern Projection

- Discretize saliency according to score
- Map onto 2D plane via longitude-latitude transformation

\[ \theta_i = \arctan\left(\frac{p_{iz}}{p_{ix}}\right) \quad \phi_i = \arctan\left(\frac{p_{iy}}{\sqrt{p_{ix}^2 + p_{iz}^2}}\right) \]
Classification using 2D Map

<table>
<thead>
<tr>
<th>Dataset</th>
<th>2D Salient map</th>
<th>LFD</th>
<th>SPH</th>
<th>D2</th>
<th>AAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>22q11.2DS</td>
<td>0.867</td>
<td>0.741</td>
<td>0.746</td>
<td>0.619</td>
<td>0.73</td>
</tr>
<tr>
<td>Plagiocephaly</td>
<td>0.803</td>
<td>0.72</td>
<td>0.673</td>
<td>0.650</td>
<td>0.685</td>
</tr>
<tr>
<td>SHREC</td>
<td>0.569</td>
<td>0.759</td>
<td>0.715</td>
<td>0.502</td>
<td>0.549</td>
</tr>
</tbody>
</table>

LFD – Light Field Descriptor
SPH – Spherical Harmonics
D2 – Shape Distribution
AAD – Angle Histogram
Retrieval using 2D Map

- Retrieval on SHREC

<table>
<thead>
<tr>
<th>2D Salient map</th>
<th>LFD</th>
<th>SPH</th>
<th>D2</th>
<th>AAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.144</td>
<td>0.097</td>
<td>0.120</td>
<td>0.361</td>
<td>0.349</td>
</tr>
</tbody>
</table>
Salient Views

- **Goal**: improve LFD by selecting only 2D salient views to describe 3D object
- Discernible and useful in describing object
Salient Views

- Silhouette with **contour salient points**
  - Surface normal vector $\perp$ camera view point

- Greedy clustering
Selecting Salient Views

• Accumulate # contour salient points
• Sort views based on # contour salient pts
• Select top K salient views

• Select top K distinct salient views (DSV)
Salient Views - Number of views

- Distinct Salient Views vs Light Field Descriptor

<table>
<thead>
<tr>
<th>No</th>
<th>Class</th>
<th># Objects</th>
<th>Avg # distinct salient views</th>
<th>Max distinct salient views score</th>
<th>LFD score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>human-diff-pose</td>
<td>15</td>
<td>12.33</td>
<td>0.113</td>
<td>0.087</td>
</tr>
<tr>
<td>2</td>
<td>monster</td>
<td>11</td>
<td>12.14</td>
<td>0.196</td>
<td>0.169</td>
</tr>
<tr>
<td>3</td>
<td>dinosaur</td>
<td>6</td>
<td>12.33</td>
<td>0.185</td>
<td>0.169</td>
</tr>
<tr>
<td>4</td>
<td>4-legged-animal</td>
<td>25</td>
<td>12.24</td>
<td>0.274</td>
<td>0.186</td>
</tr>
<tr>
<td>5</td>
<td>hourglass</td>
<td>2</td>
<td>11.50</td>
<td>0.005</td>
<td>0.001</td>
</tr>
<tr>
<td>6</td>
<td>chess-pieces</td>
<td>7</td>
<td>12.14</td>
<td>0.085</td>
<td>0.085</td>
</tr>
<tr>
<td>7</td>
<td>statues-1</td>
<td>19</td>
<td>12.16</td>
<td>0.267</td>
<td>0.250</td>
</tr>
<tr>
<td>8</td>
<td>statues-2</td>
<td>1</td>
<td>13.00</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>9</td>
<td>bed-post</td>
<td>2</td>
<td>12.00</td>
<td>0.124</td>
<td>0.008</td>
</tr>
<tr>
<td>10</td>
<td>statues-3</td>
<td>1</td>
<td>12.00</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

- Average score: 0.121 (DSV) vs 0.098 (LFD)
- Number of views: ~12 (DSV) vs 100 (LFD)
Salient Views - Runtime

- Bottleneck: feature extraction step

- Feature extraction runtime comparison

<table>
<thead>
<tr>
<th>Method</th>
<th>Setup</th>
<th>View rendering</th>
<th>Descriptor construction</th>
<th>Total time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max distinct views</td>
<td>0.467s</td>
<td>0.05s</td>
<td>0.077s</td>
<td>0.601s</td>
</tr>
<tr>
<td>LFD 100 views</td>
<td>0.396s</td>
<td>4.278s</td>
<td>4.567s</td>
<td>9.247s</td>
</tr>
</tbody>
</table>

- 15-fold speed up compare to LFD

- Reduce number of views to 10%
Learning salient points

2D longitude-latitude salient map

2D azimuth elevation histogram

Learning 3D shape quantification

3D Shape Analysis
Global 2D Azimuth-Elevation Angles Histogram

- 3D Shape Quantification for Deformational Plagiocephaly

- Classification of 22q11.2DS
3D Shape Quantification for Deformational Plagiocephaly

• Discretize azimuth elevation angles into 2D histogram

• Hypothesis: flat parts on head will create high-valued bins
Shape Severity Scores for Posterior Plagiocephaly

- Left Posterior Flatness Score (LPFS)
- Right Posterior Flatness Score (RPFS)
- Asymmetry Score (AS) = RPFS - LPFS
- Absolute Asymmetry Score (AAS)
Classification of Posterior Plagio

Absolute Asymmetry Score (AAS) vs Oblique Cranial Length Ratio (OCLR)
Classification of Posterior Plagio

Absolute Asymmetry Score (AAS) vs Oblique Cranial Length Ratio (OCLR)

# misclassified controls

<table>
<thead>
<tr>
<th>OCLR</th>
<th>AAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>2</td>
</tr>
</tbody>
</table>
Classification of Deformational Plagiocephaly

- Treat 2D histogram as feature vector
- Classify five plagiocephaly conditions
Classification of 22q11.2DS

- Treat 2D histogram as feature vector

<table>
<thead>
<tr>
<th></th>
<th>8x8</th>
<th>16x16</th>
<th>24x24</th>
<th>32x32</th>
<th>Experts’ median</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole 2D hist</td>
<td>0.651</td>
<td>0.569</td>
<td>0.79</td>
<td>0.684</td>
<td>0.68</td>
</tr>
</tbody>
</table>
## Classification of 22q11.2DS Facial Features

<table>
<thead>
<tr>
<th>Feature</th>
<th>8×8</th>
<th>16×16</th>
<th>24×24</th>
<th>32×32</th>
</tr>
</thead>
<tbody>
<tr>
<td>Midface Hypoplasia</td>
<td>0.639</td>
<td>0.744</td>
<td>0.697</td>
<td>0.651</td>
</tr>
<tr>
<td>Tubular Nose</td>
<td>0.709</td>
<td>0.593</td>
<td>0.581</td>
<td>0.663</td>
</tr>
<tr>
<td>Bulbous Nasal Tip</td>
<td>0.593</td>
<td>0.581</td>
<td>0.581</td>
<td>0.639</td>
</tr>
<tr>
<td>Prominent Nasal Root</td>
<td>0.547</td>
<td>0.639</td>
<td>0.616</td>
<td>0.658</td>
</tr>
<tr>
<td>Small Nasal Alae</td>
<td>0.561</td>
<td>0.675</td>
<td>0.571</td>
<td>0.560</td>
</tr>
<tr>
<td>Retrusive Chin</td>
<td>0.526</td>
<td>0.674</td>
<td>0.560</td>
<td>0.546</td>
</tr>
<tr>
<td>Open Mouth</td>
<td>0.875</td>
<td>0.799</td>
<td>0.844</td>
<td>0.683</td>
</tr>
<tr>
<td>Small Mouth</td>
<td>0.671</td>
<td>0.526</td>
<td>0.752</td>
<td>0.585</td>
</tr>
<tr>
<td>Downturned Mouth</td>
<td>0.613</td>
<td>0.539</td>
<td>0.553</td>
<td>0.630</td>
</tr>
</tbody>
</table>
Learning 3D shape quantification

3D Shape Analysis

2D azimuth elevation histogram

2D longitude-latitude salient map

Learning salient points
Learning 3D Shape Quantification

• Analyze 22q11.2DS and 9 associated facial features
• Goal: quantify different shape variations in different facial abnormalities
Learning 3D Shape Quantification - Facial Region Selection

• Focus on 3 facial areas
  – Midface, nose, mouth
• Regions selected manually
Learning 3D Shape Quantification - 2D Histogram Azimuth Elevation

- Using azimuth elevation angles of surface normal vectors of points in selected region
Learning 3D Shape Quantification - Feature Selection

- Determine most discriminative bins
- Use Adaboost learning
- Obtain positional information of important region on face
Learning 3D Shape Quantification - Feature Combination

• Use **Genetic Programming** (GP) to evolve mathematical expression

• Start with random population
  – Individuals are evaluated with fitness measure
  – Best individuals reproduce to form new population
Learning 3D Shape Quantification - Genetic Programming

• Individual:
  – Tree structure
  – Terminals e.g variables eg. 3, 5, x, y, …
  – Function set e.g +, -, *, …
  – Fitness measure e.g sum of square …

```
   *
  / \
 5 +
 / \
/   \
x     y
```

\[ 5^* (x+y) \]
Learning 3D Shape Quantification - Feature Combination

• 22q11.2DS dataset
  – Assessed by craniofacial experts
  – Groundtruth is union of expert scores

• **Goal**: classify individual according to given facial abnormality
Learning 3D Shape Quantification - Feature Combination

• **Individual**
  – **Terminal**: selected histogram bins
  – **Function set**: +, -, *, min, max, sqrt, log, 2x, 5x, 10x
  – **Fitness measure**: F1-measure

\[
F(prec, rec) = \frac{2 \times (prec \times rec)}{prec + rec}
\]

\[
X6 + X7 + (\text{max}(X7,X6) - \sin(X8) + (X6 + X6))
\]
Learning 3D Shape Quantification - Experiment 1

- **Objective:** investigate function sets
  - Combo1 = \{+,-,\*,\text{min},\text{max}\}
  - Combo2 = \{+,-,\*,\text{min},\text{max},\text{sqrt},\text{log2},\text{log10}\}
  - Combo3 = \{+,-,\*,\text{min},\text{max}, 2x,5x,10x,20x,50x,100x\}
  - Combo4 = \{+,-,\*,\text{min},\text{max},\text{sqrt},\text{log2},\text{log10}, 2x,5x,10x,20x,50x,100x\}
Learning 3D Shape Quantification - Experiment 1

- Best F-measure out of 10 runs

<table>
<thead>
<tr>
<th>Facial anomaly</th>
<th>Combo1</th>
<th>Combo2</th>
<th>Combo3</th>
<th>Combo4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Midface Hypoplasia</td>
<td>0.8393</td>
<td>0.8364</td>
<td><strong>0.8527</strong></td>
<td>0.80</td>
</tr>
<tr>
<td>Tubular Nose</td>
<td>0.8571</td>
<td>0.875</td>
<td>0.8667</td>
<td><strong>0.8813</strong></td>
</tr>
<tr>
<td>Bulbous Nasal Tip</td>
<td>0.8545</td>
<td>0.8099</td>
<td>0.8103</td>
<td>0.7544</td>
</tr>
<tr>
<td>Prominent Nasal Root</td>
<td>0.8667</td>
<td>0.8430</td>
<td>0.8571</td>
<td>0.8335</td>
</tr>
<tr>
<td>Small Nasal Alae</td>
<td>0.8846</td>
<td>0.8454</td>
<td>0.8454</td>
<td>0.8571</td>
</tr>
<tr>
<td>Retrusive Chin</td>
<td>0.7952</td>
<td>0.8000</td>
<td>0.7342</td>
<td>0.7586</td>
</tr>
<tr>
<td>Open Mouth</td>
<td>0.9444</td>
<td><strong>0.9714</strong></td>
<td>0.9189</td>
<td>0.9189</td>
</tr>
<tr>
<td>Small Mouth</td>
<td>0.6849</td>
<td>0.7568</td>
<td>0.6829</td>
<td><strong>0.7750</strong></td>
</tr>
<tr>
<td>Downturned mouth</td>
<td><strong>0.8000</strong></td>
<td>0.7797</td>
<td>0.8000</td>
<td>0.8000</td>
</tr>
</tbody>
</table>
Tree structure for quantifying midface hypoplasia

\[
((X7-X7) + (X6+(((X6+X6)-X7)+(X7-X2))+X7))+(X9-5X9+X7+X7)
\]

\(X_i\) are the selected histogram bins
Learning 3D Shape Quantification - Experiment 2

- **Objective**: compare local facial shape descriptors

<table>
<thead>
<tr>
<th>Facial abnormality</th>
<th>Region Histogram</th>
<th>Selected Bins</th>
<th>GP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Midface hypoplasia</td>
<td>0.697</td>
<td>0.721</td>
<td>0.853</td>
</tr>
<tr>
<td>Tubular nose</td>
<td>0.701</td>
<td>0.776</td>
<td>0.881</td>
</tr>
<tr>
<td>Bulbous nasal tip</td>
<td>0.617</td>
<td>0.641</td>
<td>0.855</td>
</tr>
<tr>
<td>Prominent nasal root</td>
<td>0.704</td>
<td>0.748</td>
<td>0.867</td>
</tr>
<tr>
<td>Small nasal alae</td>
<td>0.733</td>
<td>0.801</td>
<td>0.885</td>
</tr>
<tr>
<td>Retrusive chin</td>
<td>0.658</td>
<td>0.713</td>
<td>0.800</td>
</tr>
<tr>
<td>Open mouth</td>
<td>0.875</td>
<td>0.889</td>
<td>0.971</td>
</tr>
<tr>
<td>Small mouth</td>
<td>0.694</td>
<td>0.725</td>
<td>0.775</td>
</tr>
<tr>
<td>Downturned mouth</td>
<td>0.506</td>
<td>0.613</td>
<td>0.800</td>
</tr>
</tbody>
</table>
Learning 3D Shape Quantification - Experiment 3

- **Objective**: compare GP to global approach

<table>
<thead>
<tr>
<th>Facial abnormality</th>
<th>GP</th>
<th>Saliency Map</th>
<th>Global 2D Hist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Midface hypoplasia</td>
<td>0.853</td>
<td>0.674</td>
<td>0.744</td>
</tr>
<tr>
<td>Tubular nose</td>
<td>0.881</td>
<td>0.628</td>
<td>0.709</td>
</tr>
<tr>
<td>Bulbous nasal tip</td>
<td>0.855</td>
<td>0.616</td>
<td>0.639</td>
</tr>
<tr>
<td>Prominent nasal root</td>
<td>0.867</td>
<td>0.663</td>
<td>0.658</td>
</tr>
<tr>
<td>Small nasal alae</td>
<td>0.885</td>
<td>0.779</td>
<td>0.675</td>
</tr>
<tr>
<td>Retrusive chin</td>
<td>0.800</td>
<td>0.628</td>
<td>0.674</td>
</tr>
<tr>
<td>Open mouth</td>
<td>0.971</td>
<td>0.707</td>
<td>0.875</td>
</tr>
<tr>
<td>Small mouth</td>
<td>0.775</td>
<td>0.581</td>
<td>0.752</td>
</tr>
<tr>
<td>Downturned mouth</td>
<td>0.800</td>
<td>0.566</td>
<td>0.630</td>
</tr>
</tbody>
</table>
# Learning 3D Shape Quantification - Experiment 4

- **Objective**: predict 22q11.2DS

<table>
<thead>
<tr>
<th>Method</th>
<th>F-measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantification vector with SVM</td>
<td>0.709</td>
</tr>
<tr>
<td>Quantification vector with Adaboost</td>
<td>0.721</td>
</tr>
<tr>
<td>Quantification vector with GP</td>
<td>0.821</td>
</tr>
<tr>
<td>Global saliency map</td>
<td>0.764</td>
</tr>
<tr>
<td>Selected bins of global saliency map</td>
<td>0.9</td>
</tr>
<tr>
<td>Global 2D histogram</td>
<td>0.79</td>
</tr>
<tr>
<td>Selected bins of global 2D histogram</td>
<td>0.9</td>
</tr>
<tr>
<td>Selected bins of global saliency map with GP</td>
<td>0.96</td>
</tr>
<tr>
<td>Selected bins of global 2D histogram with GP</td>
<td>0.92</td>
</tr>
<tr>
<td>Expert’s median</td>
<td>0.68</td>
</tr>
</tbody>
</table>
Outline

• Related Literature
• Datasets
• Base Framework
• 3D Shape Analysis
• Conclusion
Contributions

• General methodology for 3D shape analysis
• Learning approach to detect salient points
• 3D object signatures
  – 2D longitude-latitude salient map
  – 2D histogram of azimuth-elevation angles
• Methodology for quantification of craniofacial disorders
Future Directions

• Analyze other craniofacial disorders
  – Cleft lip/palate, craniofacial microsomia
• Association of shape changes
  – Over time, pre/post op
• Genotype–phenotype disease association
• Translate 3D shape quantification into plain English language
Acknowledgements

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  – Linda Shapiro; James Brinkley; Maya Gupta; Mark Ganther; Steve Seitz

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  – Michael Cunningham; Matthew Speltz; Brent Collett; Carrie Heike; Christa Novak

• Research Group

• This research is supported by the National Science Foundation under grant number DBI-0543631
Publications

[1] 3D Head Shape Quantification for Infants with and without Deformational Plagiocephaly.
Accepted for publication in *The Cleft-Palate Craniofacial Journal*, 2009.

[2] 3D Object Classification using Salient Point Patterns With Application to Craniofacial Research
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