Multi-Scale Contour Extraction Based on Natural Image Statistics

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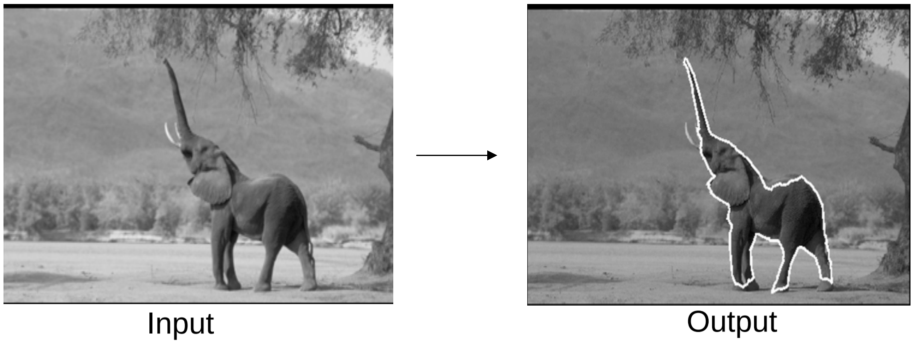
Problem

- Compute bounding contours of salient objects in a natural image



Input Output

Single vs. Multi-Scale

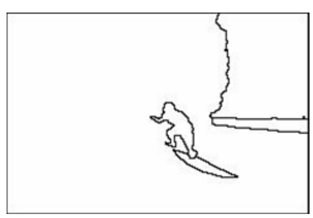
- Most approaches: single scale
  - Work at highest level of detail
  - “miss the forest for the trees”
- Estrada & Elder approach: multi-scale
  - Coarse to fine approach
  - Reduces complexity

Training & Test Data

Berkeley Segmentation Database

12,000 hand-labeled segmentations of 1,000 images by 30 human subjects.

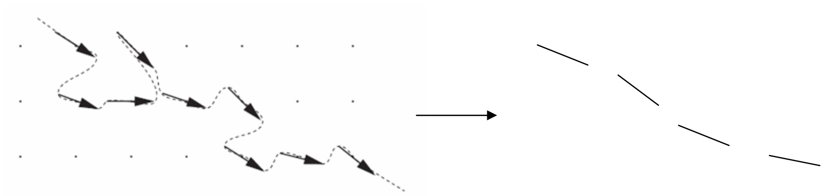
Training:	37 / 200 images
Test :	20 / 100 images



- At least one salient, unoccluded object contained within image bounds
- Human produced ground truth

First Steps

- Detect edges (See Elder and Zucker, 1998b)
- Convert to tangent representation (line segments)



Definitions

$T = \{t_1, ..., t_N\}$ Set of tangents (line segments)

T^o Subset of tangents on boundaries of objects of interest

$s = \{t_{\alpha_1}, ..., t_{\alpha_m}\}$ Sequence of tangents

C Subset of possible sequences that correspond to actual contours in image

C^0 Subset of these sequences that lie on boundaries of objects of interest

Definitions

$$s = \{t_{\alpha_1}, \ldots, t_{\alpha_m}\}$$

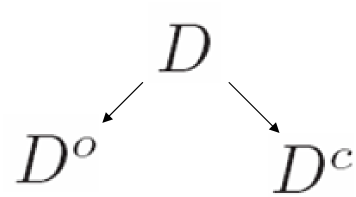
Sequence of tangents

$$I_1^o = \{\alpha_1, \ldots, \alpha_m\}$$

Set of tangent indices for current hypothesis *s*

$$I_1^c = \{\{\alpha_1, \alpha_2\}, \ldots, \{\alpha_{m-1}, \alpha_m\}\}$$

Set of index pairs for directly successive tangents in *s*



Observable cues (data)

Unary object cues

Binary grouping cues (pairwise)

Definitions

Posterior probability of the hypothesis:

$$p(s \in C^0 | D) \;\; \alpha \;\; F(s, D) = \prod_{i \in I_1^o} p_i^o \prod_{\{i,j\} \in I_1^c} p_{ij}^c, \qquad (1)$$

p_i^o — Posterior probability that tangent t_i lies on an object of interest

p_{ij}^c — Posterior probability that tangents t_i and t_j are directly successive tangents on a real contour

$F(s, D)$ — Foreground term

Definitions

$$p_i^o = \frac{1}{1 + (L_i^o P_i^o)^{-1}} \quad \text{and} \quad p_{ij}^c = \frac{1}{1 + (L_{ij}^c P_{ij}^c)^{-1}},$$

$$L_i^o = \prod_{k=1}^{m^o} \frac{p(d_i^k | t_i \in T^o)}{p(d_i^k | t_i \notin T^o)} \qquad L_{ij}^c = \prod_{k=1}^{m^c} \frac{p(d_{ij}^k | \{t_i, t_j\} \in C)}{p(d_{ij}^k | \{t_i, t_j\} \notin C)}$$

m^o- set of unary cues m^c - set of binary cues

d_i^k - observed value of k^{th} unary cue at tangent t_i

d_{ij}^k - observed value of k^{th} binary cue for pair of tangents $\{t_i, t_j\}$

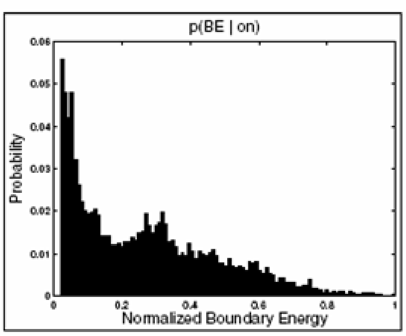
$$P_i^o = \frac{p(t_i \in C)}{p(t_i \notin C)} \qquad P_{ij}^c = \frac{p(\{t_i, t_j\} \in C)}{p(\{t_i, t_j\} \notin C)}.$$

Background

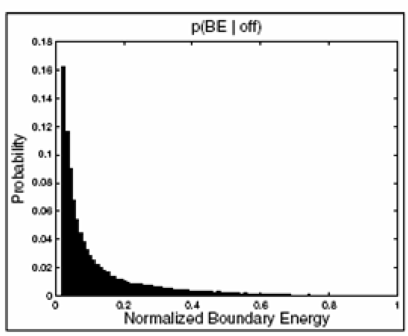
Unary cues measure salience of individual tangents

Compute “boundary energy” (Martin et al) at each pixel based on:

- Brightness, color, and texture



Probability distributions for boundary energy ON ground truth contours



Probability distributions for boundary energy OFF ground truth contours

Background

Binary cues (pairwise between two tangents) measure:

- Proximity
- Smooth continuation
- Similarity of brightness/contrast between pair of tangents

Learned from natural scene statistics
(Elder and Goldberg, 2002)

Single Scale Grouping Algorithm

1. Start with a set of tangents
2. Keep a table of *M* best possible continuations for each tangent
3. Iteratively expand list of hypotheses

Single Scale Grouping Algorithm

Iterate:

- For each of the *K* current hypotheses of length *l*, generate a set of *M* expanded contours of length *l* + 1 by adding to that hypothesis one of the *M* tangents in its list of best continuations
- Remove any self-intersecting or duplicate contours
- Compute the term *F*(*s,D*) for each of the remaining hypotheses
- Sort the new set of hypotheses, and keep only the *K* contours with the highest *F*(*s,D*)
- Detect and store any closed contours found among the new hypotheses

Terminate:

- When none of current hypotheses can be expanded

Evaluate:

- All closed contours sorted in order of decreasing "quality" (geometric mean of F(s,D))

Single Scale Grouping Algorithm

- Quality of a given contour determined by geometric mean of $F(s, D) = \prod_{i \in I_1^o} p_i^o \prod_{\{i,j\} \in I_1^c} p_{ij}^c,$

For contour length γ geometric mean = $F(s_k|D)^{1/\gamma}$

$$\log(F(s_k|D)^{1/\gamma}) = \frac{\sum_{t_i \in s_k} \log(p_i^o) + \sum_{\{t_i,t_j\} \in s_k} \log(p_{ij}^c)}{\gamma}$$

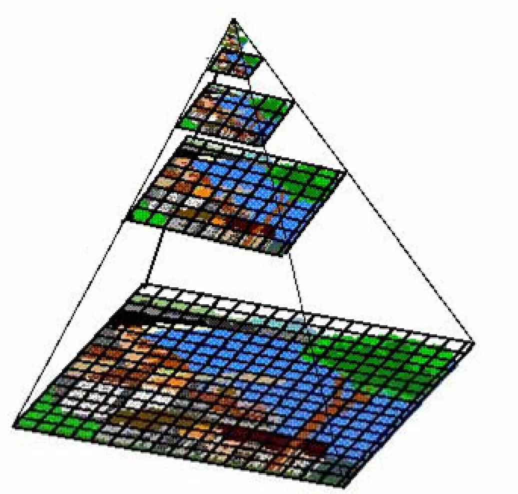
Multi Scale Grouping Algorithm

General Idea:

- Start at coarse scale
- Refine until detailed contours achieved at finer scales

Multi Scale Grouping Algorithm

- Generate W level pyramid
- For each image, detect edges and fit line segments
- Yields W sets of tangents that are input to multi-scale algorithm



Gaussian Pyramid

Multi Scale Grouping Algorithm

1. Run single scale algorithm at coarsest level
2. The best P contours are stored and used as priors for the next scale
3. Run algorithm P + 1 times at next scale
4. Repeat until contours at highest resolution obtained

Multi Scale Grouping Algorithm

Using coarse contours as a spatial prior

Two tasks:

- Need contour representation that can be easily transported across scales
- Need to study relationship between coarse and fine scale contours to derive appropriate statistical distributions

Multi Scale Grouping Algorithm

Contour Representation:

Model contours using Fourier descriptors
(See Staib, L. H., and Duncan, J. S., 1992)

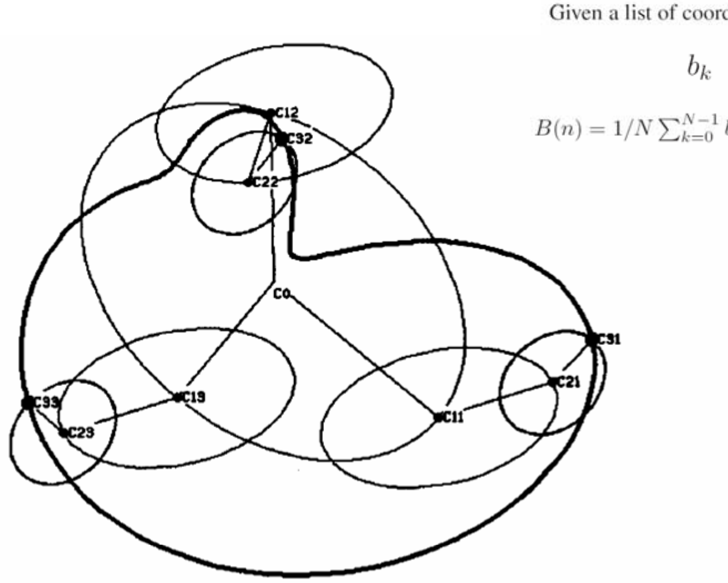
- Transfers contours across scales
- Added bonus - smoothes out noise and discretization artifacts

Fourier Shape Descriptors

Given a list of coordinates (x_k, y_k) for $k = 0, \dots, N-1$

$$b_k = x_k + iy_k$$

$$B(n) = 1/N \sum_{k=0}^{N-1} b(k) e^{-ik2\pi n/N} \text{ for } n = 0, \dots, N-1$$



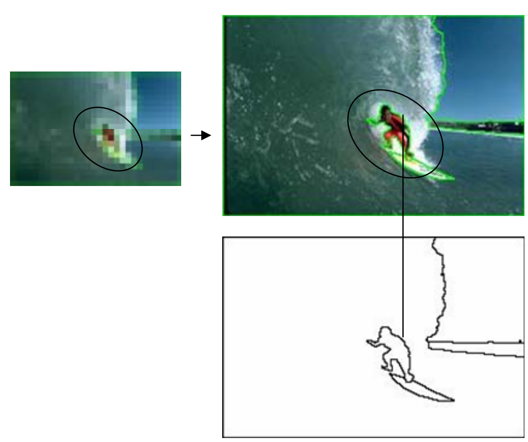
Multi Scale Grouping Algorithm

- Generate Fourier model, project reconstruction scaled by 2X onto image at next finer scale
- Grouping algorithm should favor lines whose orientation and spatial location match projected contour

Multi Scale Grouping Algorithm

Building the Spatial Prior

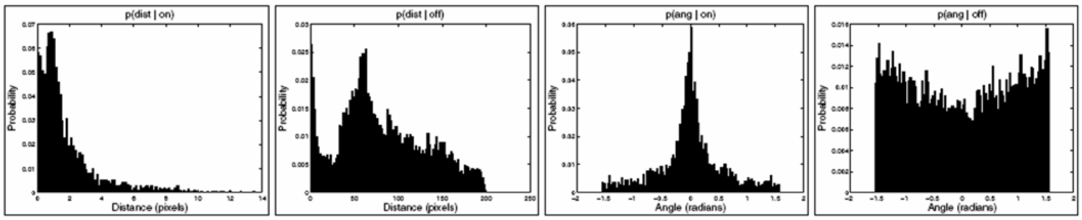
- Generate Fourier model for lower resolution ground truth contours
- Project onto image of highest resolution
- Measure deviation in position and orientation between the scaled Fourier contours and the ground truth contours at the fine scale



Multi Scale Grouping Algorithm

Estimate four probability distributions

On contour | Off contour | On contour | Off contour



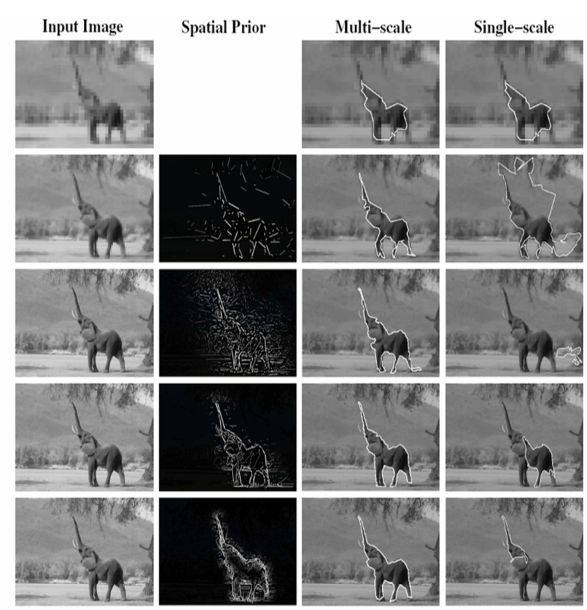
Characterizes distance between ground truth tangents and scaled contour

Characterizes difference in orientation between ground truth tangents and scaled contour

Results

Coarse

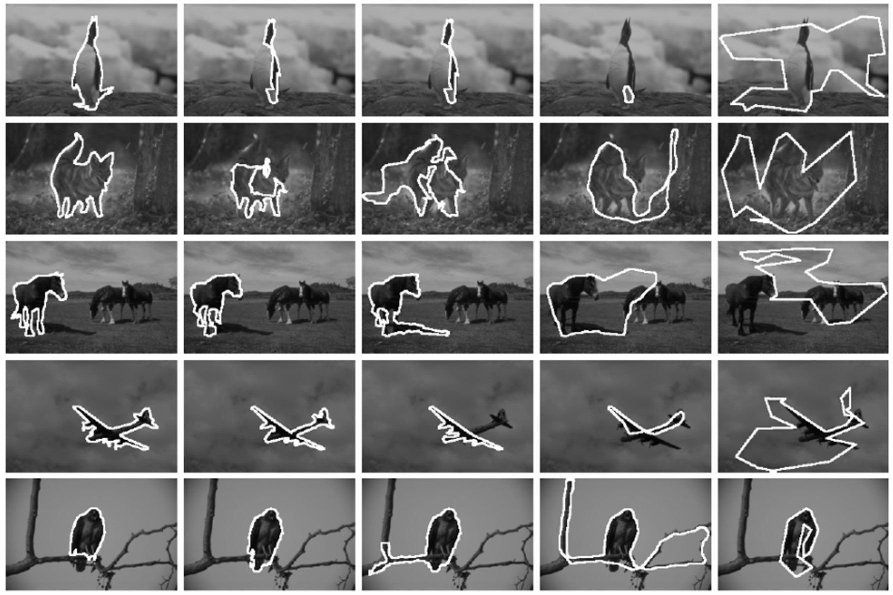
Fine
737x486



Complete run of multi scale algorithm

Comparison

Best contours extracted by several algorithms



Conclusions

- Multi scale approach outperforms single scale and other methods
  - Coarse contours capture general shape, refined until detailed contours obtained at finest scale
  - Captures complex boundaries where single scale approach fails
  - Provides robustness to texture and clutter
- Room for improvement:
  - Better contour quality metric than geometric mean
  - Degraded performance at high resolutions
  - Add global shape prior based on natural scene statistics

Questions?