Interactive Live-Wire Boundary Extraction

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   - Overview
   - Motivation
2. Proposed Method
   - Overview
   - Problem Formulation
   - Cost Function
     - Gradient Magnitude Feature $f_G(q)$
     - Laplacian Zero-Crossing Feature $f_Z(q)$
     - Gradient Direction Feature $f_D(p, q)$
   - Segmentation Walkthrough
   - Advantages of Wavefront Propagation
3. Other Features
   - Boundary Freezing
   - On-The-Fly Learning
   - Data-Driven Path Cooling
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   - Qualitative Results
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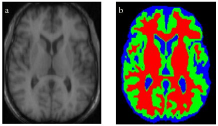
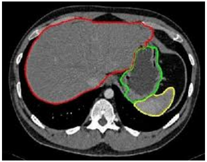
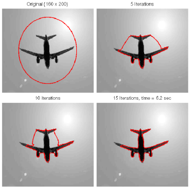
Problem Statement

Overview : Image Segmentation

- Image segmentation is the broad task of delineating objects/boundaries/edges/contours of interest in a 2D/3D image.
- In context of medical imaging, it is the process of extracting particular regions of interest (ROIs) from a medical image (CT/XRAY/MRI/Mammogram), which can be :
    - Tumors
    - Tissue sub-types
    - Organs
- A variety of image types and contents make fully-automated segmentation an unsolved problem.
- Most techniques require significant user input to specify ROIs, or to initialize contours.







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Previous Work and Motivation

Previous Work and Outstanding Issues

- Earlier segmentation approaches used *local* boundary-defining criteria [1] [2]
  - Susceptible to noise
- Others incorporated global identifiers [3]
  - 1D implementations introduced restrictions on sampling and searching, requiring 2D templates.
  - Required high degree of user interaction, while tied to particular domain constraints.
  - Highly computational.
- Another set of methods based on Snakes [4] were introduced.
  - Dependent on initial contour, required high user interaction.
  - Final boundary couldn't be visualized until energy minimization is finished.

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1. O'Brien, J.F. and Ezquerra, N.F. (1994) Automated Segmentation of Coronary Vessels in Angiographic Image Sequences Utilizing Temporal, Spatial and Structural Constraints. Visualization in Biomedical Computing '94, SPIE Vol. 2359, pp. 25-37
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3. Montanari, U. (1971) On the Optimal Detection of Curves in Noisy Pictures. Comm. ACM, 14, 335-345
4. Kass, M., Witkin, A. and Terzopoulos, D. (1987) Snakes : Active Contour Models. Proc. First International Conference on Computer Vision, pp. 259-68.

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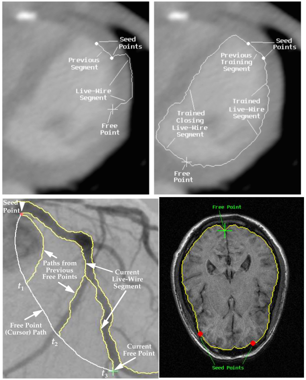
Live-Wire Interactive Boundary Extraction

Method Overview

- Live-Wire interactive boundary extraction is a tool for efficient, accurate and reproducible segmentation.
- Boundary detection is formulated as a graph-searching problem.
  - Find a path with least cumulative cost from seed pixel to goal pixel.
- Allows minimal user input in the form of a starting seed point and a free floating point which follows the mouse cursor.
- Introduces concepts of “freezing" and “data-driven path cooling", which reduces effective user interaction by a large magnitude.
- Supports “on-the-fly learning" which allows user to segment areas where local information does not support correct segmentation due to minimas corresponding to other locations.



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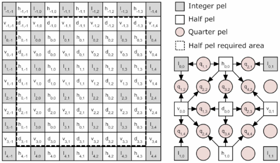
Live-Wire Graph-Search Formulation

Overview

- Live-Wire reformulates the problem of boundary detection as an “optimal" path searching problem from a seed point (A) to a goal point (B).
- The path is “optimal" if the path has a lowest minimum cumulative “cost" from all possible paths between point A and B.
  - Problem then collapses to a “shortest path" finding problem, taking account node costs.
- Live-Wire defines a cost function which is used to associate costs to each particular node in the graph.
- User supplies the seed node, from which an optimal path is extended dynamically, and in near interactive speed, to any free point (goal point) denoted by the position of cursor on the screen.



a) b)

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Node Cost Function

Overview

- The cost function $l(p, q)$ is defined by Live-Wire to associate weights to each directed link between two nodes (pixels) p and q in the image is as follows :

$$l(p, q) = w_G . f_G(q) + w_Z . f_Z(q) + w_D . f_D(p, q) \tag{1}$$

- The cost function is made of three terms :
  - $f_G(q)$ = Gradient Magnitude feature
  - $f_Z(q)$ = Laplacian Zero-Crossing feature
  - $f_D(p, q)$ = Gradient Direction feature
- The coefficients $w_i \forall i \in G, Z, D$ have values : $w_G = 0.43$, $w_z = 0.43$, $w_D = 0.14$.

Gradient Magnitude Feature $f_G(q)$

- Provides a “first-order" positioning of live-wire boundary as a measure of edge strength.
- High image gradients must correspond to lower cost, hence an inverse linear ramp function is used :

$$f_G = 1 - \frac{G}{max(G)} \tag{2}$$

- where G = gradient magnitude and $max(G)$ is the maximum gradient magnitude observed so far.

Laplacian Zero-Crossing Feature $f_Z(q)$

- The second cost term $f_Z(q)$ is a binary “second-order" term representing edge features.

$$^{5}f_z(q) = \begin{cases} 0 & \text{if} \quad I_L(q) = 0 \\ & \text{or} \quad sgn(I_L(q_t))! = sgn(I_L(q)), \quad \forall q_t \in \{\text{8-connected neighbours of q}\} \\ 1 & otherwise \end{cases} \tag{3}$$

- Where $I_L = I(x, y) * LOG_{kernel}$ where $*$ is the convolution operation and LOG_{kernel} is a Laplacian of Gaussian kernel. $sgn(.)$ is a signum function which extracts the sign of it's argument.
- $I(x, y)$ is the original image, and $q \in I$ is a pixel in image I.
- $f_Z(q)$ has low cost (zero) corresponding to good edges or zero crossings.

5. mathematical depiction of the function was not presented in original paper

Gradient Direction Feature $f_D(p,q)$

- Gradient Direction feature adds a smoothness constraint to the cost, where high changes in direction exhibits higher cost.
- This forces the contour to follow the path where changes in gradient direction is subtle.

$$f_D(p,q) = \frac{2}{3\pi}\left[cos\left(\frac{1}{d_p(p,q)}\right) + cos\left(\frac{1}{d_q(p,q)}\right)\right] \tag{4}$$

- where $d_p(p,q) = D(p).L(p,q)$ and $d_q(p,q) = L(p,q).D(q)$, and

$$L(p,q) = \begin{cases} q-p & \text{if} \quad D(p).(q-p) >= 0 \\ p-q & \text{if} \quad D(p).(q-p) < 0 \end{cases} \tag{5}$$

- $L(p,q)$ is a horizontal, vertical, or diagonal link vector which ensures that $d_p(p,q)$ is always positive and <= $\pi/2$.
- $L(p,q)$ can be interpreted as the relative position of q in p's 8-connected neighbourhood.
- The overall cost $f_D(p,q)$ is low when gradient direction of two pixels are similar to each other and *the link between them*.

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Example Segmentation

Walkthrough

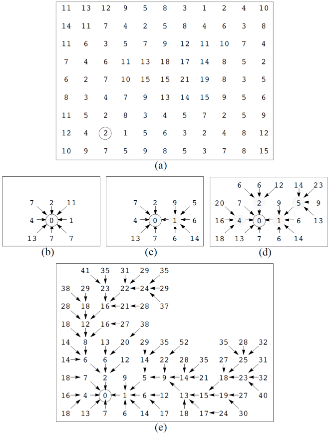

FIGURE – a) Original local cost with seed point circled, b) expansion of seed point and propagation of cost, c) example of further propagation using point of minimal cost, d) wavefront propagation in the image

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Advantages of Wavefront Propagation

- Spontaneous wavefront propagation allows path expansion to keep up with path selection.
  - This makes interactively selected paths immediately available.
- Computationally much faster than other DP based techniques requiring n computations in cost matrix with path length = n.
- Due to highly interactive nature, optimal path changes according to final free point chosen by cursor.

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Boundary Freezing

Overview

- Live-wire segmentation may digress from the desired object boundary during interactive mode.
- The boundary can be “frozen" right before the digression point by specifying another seed point, until which the boundary is frozen and not allowed to be changed.
- The new seed point marks the initial point of another piece of the boundary, from which expansion occurs.

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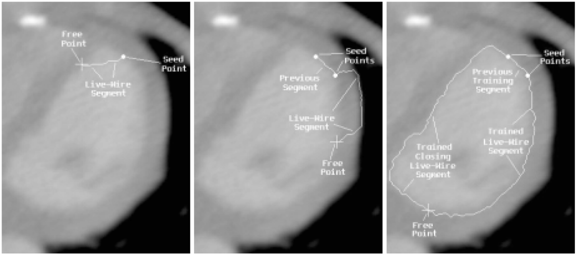
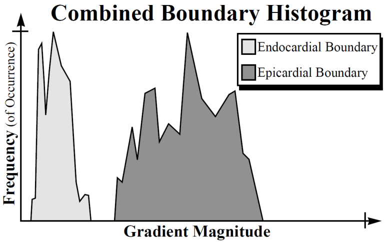
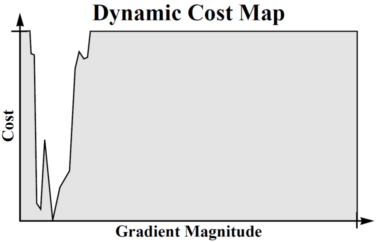
On-The-Fly Learning

Overview







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Data-Driven Path Cooling

Overview

- Manual path freezing is performed by setting a new seed point from which a new live-wire is initialized, and earlier one is frozen.
- However this is still a manual process.
- Data-driven path cooling allows the live-wire to generate new seed points automatically as a function of image data and path properties.
- Particularly, the two factors leading to “cooling" of a path are :
  - Path stability : Time on the active boundary,
  - Path coalescence : Number of times the path has been drawn from distinct seed points.
- Pixels on stable paths will cool down and eventually freeze, producing new seed points.

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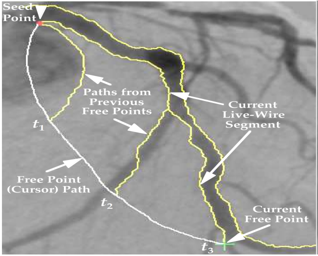
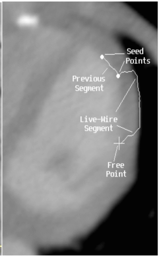
Segmentation Results

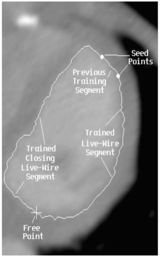
- Qualitative results are presented on medical images like CT, X-ray angiography, MRI and color photograph from Visible Human Project.
- Average time (in seconds) and number of seed points used to extract the boundary are reported for each example.

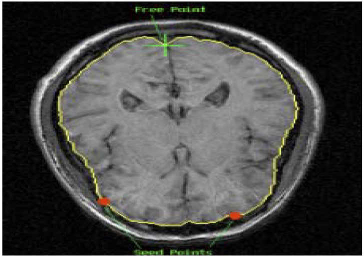
Segmentation Results

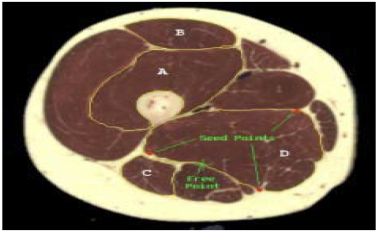
Qualitative Results











Segmentation Results

Qualitative Results

Figure	Anatomy	Time (s)	Seed points	Training used	Cooling used
2	Coronary (right side)	2.02	2	N	N
	Coronary (left side)	3.50	3	N	N
3	Left ventricle	3.71	2	Y	N
4	Brain	2.30	3	Y	Y
5	Lumber spine	5.90	4	N	Y
6	Thigh muscle A	6.40	5	N	N
	Thigh muscle B	1.33	2	N	N
	Thigh muscle C	1.31	2	N	N
	Thigh muscle D	3.24	3	N	N
	Average:	3.30	2.89		

- The average times using Live-Wire was roughly 4.6 times less than manual human tracing time.
- Live-Wire provides same amount of accuracy as manual tracing would in a fraction of time, with high reproducibility.

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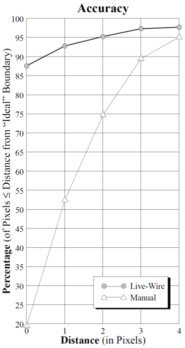
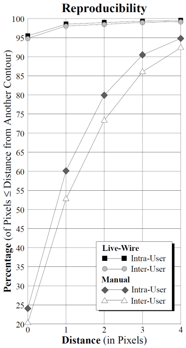
Quantitative Segmentation Results

Metrics





- Accuracy with Live-Wire was 4.4 times higher than manual.
- For both inter- and intra-observer, the reproducibility was reported to be very high (>=95%).

Critique

- The method does not provide a way to “snap out" of an *automatically* frozen live-wire segmentation.
- On-the-fly training can fail at instances where the edges of the object change too fast.
- Not much implementation related information is provided, especially for freezing and training parts.
- No qualitative/quantitative results on noisy images, which can impair gradient based cost functions.
- Number of times boundary extraction was performed to calculate inter- (5 times) and intra-observer (3 times) rates was not similar, which can skew the intra-observer rate.

Thank You!

Questions ?