A Novel Edge-Preserving Mesh-Based Method for Image Scaling

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Outline

- Image scaling problem
- Introduction to triangle-mesh models of images
- Proposed image scaling method
- Results
- Conclusions

Image Scaling Problem

- Image $I_{W \times H} \rightarrow \boxed{\text{scale with factor } \alpha > 1} \rightarrow$ scaled image $I_{\alpha W \times \alpha H}$
- Different image scaling methods:
  1. Raster-based: using pixels $\Rightarrow$ bilinear, bicubic, ...
  2. Vector-based: using geometric primitives $\Rightarrow$ triangle-mesh models

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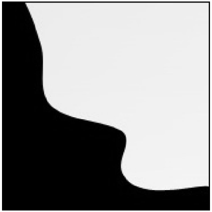
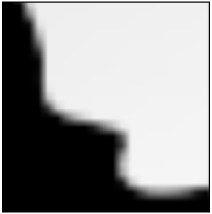
- Different image scaling methods:
  1. Raster-based: using pixels $\Rightarrow$ bilinear, bicubic, ...
  2. Vector-based: using geometric primitives $\Rightarrow$ triangle-mesh models
- Raster-based methods often suffer from severe edge blurring

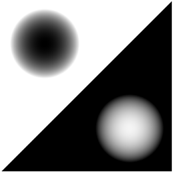

original


bilinear, $\alpha = 8$

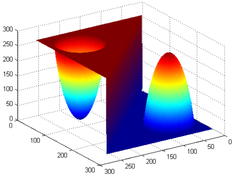

bicubic, $\alpha = 8$

- Goal: produce scaled image with better subjective quality

Triangle Mesh Models of Images



original image ϕ



surface model

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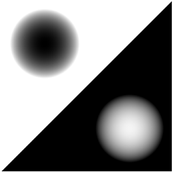

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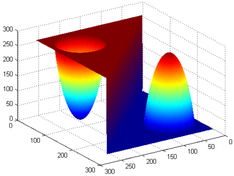

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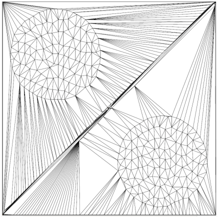
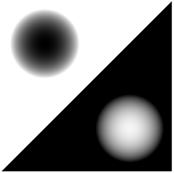
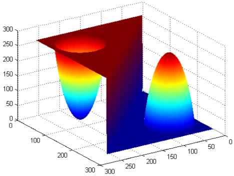


triangulation

Triangle Mesh Models of Images



original image ϕ



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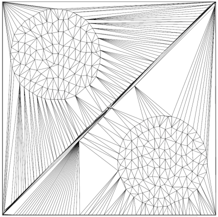
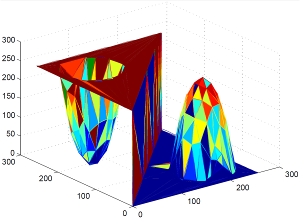
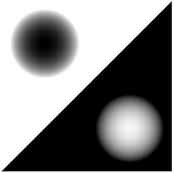


triangulation

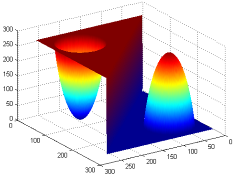


triangle-mesh model

Triangle Mesh Models of Images



original image ϕ



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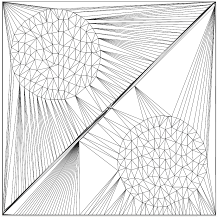

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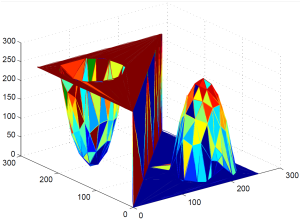
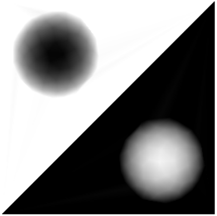


triangle-mesh model



reconst. image ϕ'

ERD Mesh Model

- Originally proposed by Tu and Adams in 2013
- Explicit representation of discontinuities (ERD)
- Discontinuous and piecewise-linear approximating function
- Based on constrained Delaunay triangulation (CDT)

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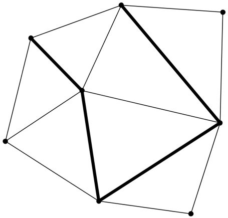

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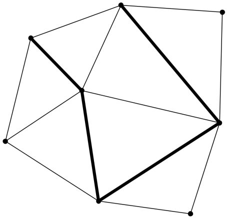
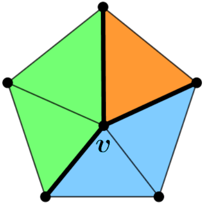


CDT



three wedges

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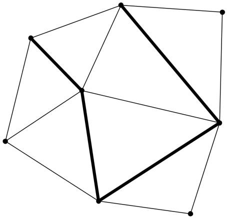

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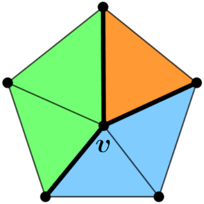

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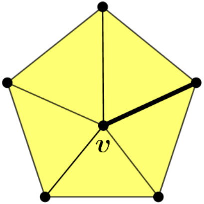
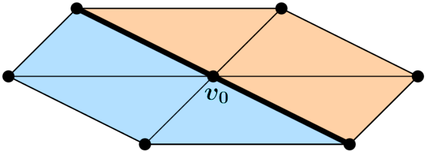


one wedge

ERD Mesh Model Cont'd

How is image discontinuity (edges) modeled?

- Each wedge is associated with a *wedge value*
- Wedge values are used to create approximating function



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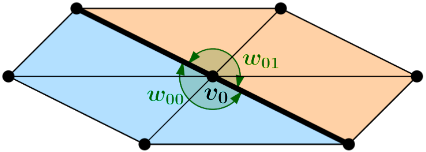

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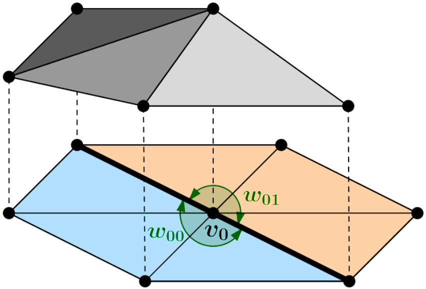

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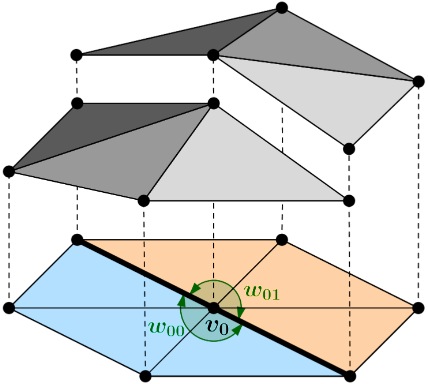

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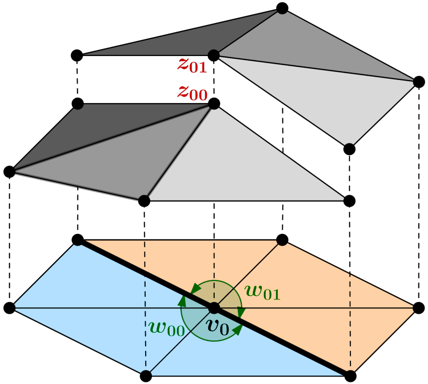

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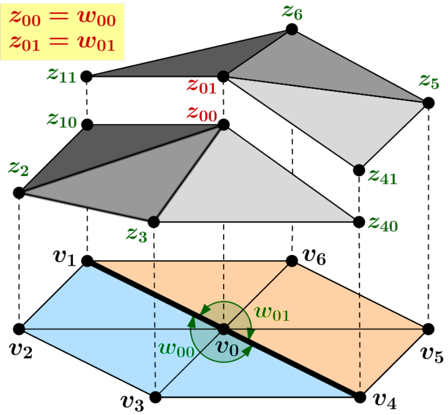

Mesh-Generation Method

- ERD mesh model parameters:
  1. Set of sample points, $P = \{v_i\}$
  2. Set of edge constraints, E
  3. Set of wedge values, Z

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  1. Set of sample points, $P = \{v_i\}$
  2. Set of edge constraints, E
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- The process to select model parameters is called **mesh generation**
- Image $\phi \rightarrow \boxed{\text{mesh generation}} \rightarrow P$, E, and Z
- Image resolution of $W \times H$
- Sampling density of mesh, $d = \dfrac{|P|}{W \times H} \times 100$

Proposed Image Scaling Method

- Two steps:

    1. Input image $\rightarrow$ $\boxed{\text{mesh generation}}$ $\rightarrow$ ERD mesh model

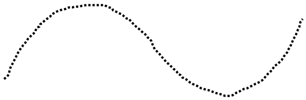
    2. ERD mesh model $\rightarrow$ $\boxed{\text{image reconstruction}}$ $\rightarrow$ scaled image

Proposed Image Scaling Method Cont'd

Step 1: Mesh Generation

Select model parameters (i.e., P, E, Z) with N samples:

1. Initial triangulation:
   - Detect image edges (Canny edge detector)
   - Edges approximated with polylines: P_0 and E
   - Constrained Delaunay triangulation with P_0 and E



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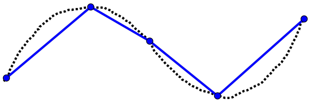

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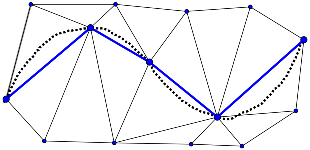

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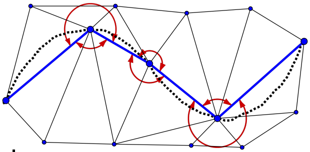


2. Calculate initial wedge values

Proposed Image Scaling Method Cont'd

Step 1: Mesh Generation

Select model parameters (i.e., P, E, Z) with N samples:

1. Initial triangulation:
    - Detect image edges (Canny edge detector)
    - Edges approximated with polylines: P_0 and E
    - Constrained Delaunay triangulation with P_0 and E
2. Calculate initial wedge values
3. Select new point q to add to mesh
4. Insert q into mesh
5. Recalculate wedge values
6. Repeat steps 3 to 5 until $|P| = N$

Image reconstruction contains two steps:

1. Mesh Refinement: to produce smoother edge curves and image function
    - Mesh is refined iteratively through a subdivision process
    - A variation of the Loop subdivision (proposed by Liao et. al. in 2012)
    - Three steps of subdivision is used
2. Mesh Rasterization:
   Rasterize the (subdivied) mesh to a finer grid $\rightarrow$ scaled image

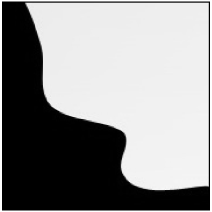
Evaluation Methodology

Assume image I and scale factor $\alpha > 1$:

1. $I \rightarrow \boxed{\text{reduce resolution by factor } 1/\alpha} \rightarrow I_{low}$
2. $I_{low} \rightarrow \boxed{\text{scaling method to increase resolution by factor } \alpha} \rightarrow I'$
3. Compare I' with I with:
   - Subjective: visual inspection
   - Objective: percentage edge error (PEE) metric
4. Compared with **bilinear** and **bicubic** methods

Evaluation Results: Scale Factor $\alpha = 8$

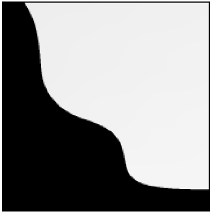
hi-res image I



I (zoomed)

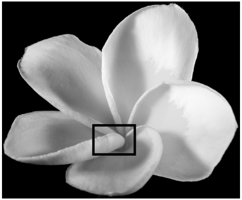
bilinear,PEE=55.17

bicubic,PEE=47.58



propos., PEE=0.95, d=2%

Evaluation Results: Scale Factor $\alpha = 4$

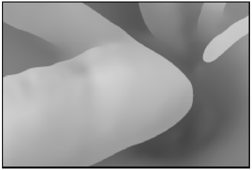


hi-res image I

I (zoomed)

bilinear, PEE=19.25

bicubic, PEE=11.22



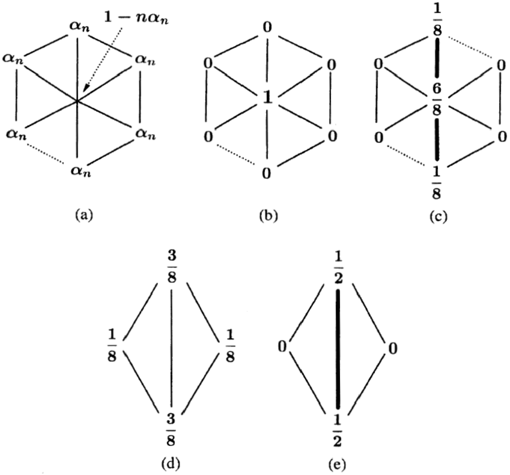
proposed, PEE=-0.42, d=4%

Conclusions

- A novel mesh-based method proposed for image scaling
- Proposed method uses a mesh model which explicitly represents discontinuities
- Proposed method can:
  - effectively preserve the sharpness at edges
  - create scaled images of higher quality to human eyes
- Proposed method outperforms the commonly-used bilinear and bicubic methods
- Our method can benefit many applications in digital photography, computer graphics, and medical imaging

THANK YOU

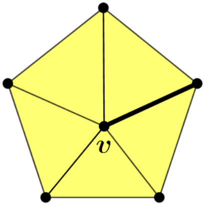
Modified Loop Subdivision Masks



$\alpha_n = \frac{1}{n}[\frac{5}{8} - (\frac{3}{8} + \frac{1}{4}\cos\frac{2\pi}{n})^2]$, when n is the valence of the vertex

Two types of vertices:

1. Zero or one constrained edge: $z = \phi(v)$



Proposed Image Scaling Method Cont'd

1-Mesh Generation: Wedge-Value Calculation

Two types of vertices:

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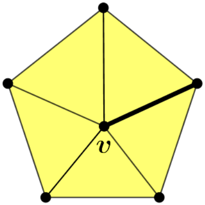
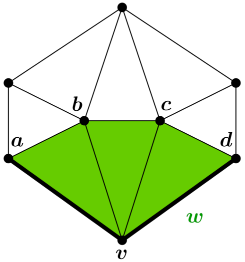


2. More than one constrained edges: backfilling-based approach

Backfilling-based method:

- Wedge value z for wedge w associated with vertex v
- S: vertices connected to v in w, not incident on constrained edges
- Values at points near edges are not reliable (blurred zone)



$S = \{b, c\}$

$z = \frac{1}{|S|} \sum_{p \in S} \phi(p)$

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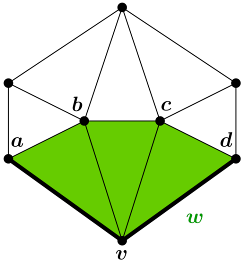

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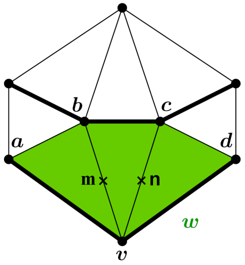

$S = \{\emptyset\}$
$z = \frac{\phi(m)+\phi(n)}{2}$

Point q to be inserted in mesh is selected in 2 steps:

1. Select face f^* with highest squared error as

$$f^* = \operatorname*{argmax}_{f \in F} \sum_{p \in \Omega_f} \left(\hat{\phi}(p) - \phi(p) \right)^2$$

Ω_f: all valid points in face f
Valid point: NOT 8-connected pixels of any image edges
F: all faces for which $\Omega \neq \{\emptyset\}$

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   Ω_f: all valid points in face f
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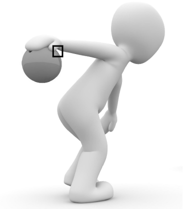
2. Select q as the point with the highest absolute error in f^* as

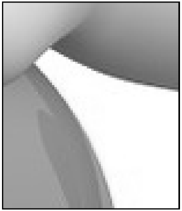
$$q = \operatorname*{argmax}_{p \in \Omega_{f^*}} \left| \hat{\phi}(p) - \phi(p) \right|$$

Evaluation Results Cont'd

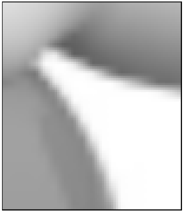
Test Image 2 with $\alpha = 4$



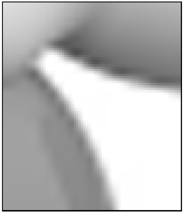
Original



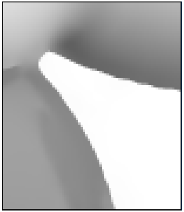
Orig. Magnified



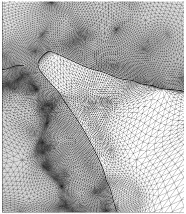
Bilin.,PEE=27.51



Bicub.,PEE=18.44



Prop.,PEE=0.18

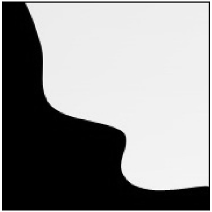


Mesh @ 2%

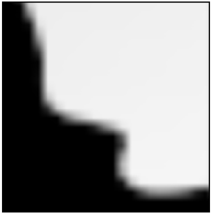
Evaluation Results Cont'd

Test Image 1 with $\alpha = 8$

Original

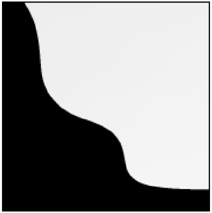


Original Magnified

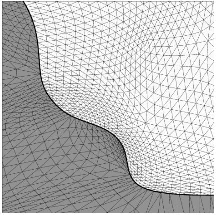


Bilinear,PEE=55.17

Bicubic,PEE=47.58



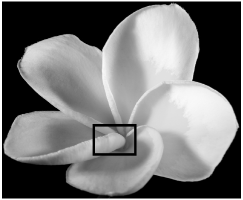
Propose,PEE=0.95



Mesh @ 2%

Evaluation Results Cont'd

Test Image 3 with $\alpha = 4$

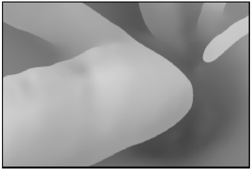


Original

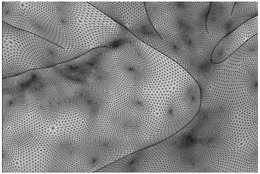
Original Magnified

Bilinear,PEE=19.25

Bicubic,PEE=11.22



Proposed,PEE=-0.42



Mesh @ 4%