Seamless: Seam erasure and seam-aware decoupling of shape from mesh resolution

Songrun Liu*, George Mason University
**Zachary Ferguson**, George Mason University
Alec Jacobson, University of Toronto
Yotam Gingold, George Mason University
(*Joint first authors)
TEXTURES

Color Map

Normal Map

Displacement Map

Geometry Images [Gu et al. 2002]
TEXTURE MAPPING
TEXTURE MAPPING
TEXTURE MAPPING
2D PARAMETERIZATION
2D PARAMETERIZATION
2D PARAMETERIZATION
SEAMS
SEAMS
SEAMS
SEAM DISCONTINUITIES
SEAM DISCONTINUITIES
SEAM DISCONTINUITIES
SEAM DISCONTINUITIES
SEAM DISCONTINUITIES
SEAM DISCONTINUITIES
DISCONTINUITIES IN GEOMETRY IMAGES

Before

After
DISCONTINUITIES IN GEOMETRY IMAGES

Before

After
DISCONTINUITIES IN GEOMETRY IMAGES
CONTRIBUTIONS
CONTRIBUTIONS

Seam Erasure
CONTRIBUTIONS

Seam Erasure

Seam Aware Decimation
CONTRIBUTIONS

Seam Erasure

Seam Aware Decimation

Seam Straightener
CONTRIBUTIONS

Seam Erasure

Seam Straightener

Seam Aware Decimation

Weight Maps
CONTRIBUTIONS

Seam Erasure

Seam Aware Decimation

Seam Straightener

Weight Maps
OVERVIEW

INPUT:

OUTPUT:
OVERVIEW

INPUT:

OUTPUT:
OVERVIEW

INPUT:

OUTPUT:
OVERVIEW

INPUT:

OUTPUT:
RELATED WORKS
RELATED WORKS

Control the Parameterization

[Aigerman et al. 2015]  [Kovalsky et al. 2016]  [Myles and Zorin 2013]  [Purnomo et al. 2004]  [Ray et al. 2010]
RELATED WORKS

Control the Parameterization

[Aigerman et al. 2015]  [Kovalsky et al. 2016]  [Myles and Zorin 2013]  [Purnomo et al. 2004]  [Ray et al. 2010]

Modify Rendering Pipeline

[Toth 2013]  [Piponi and Borshukov 2000]
RELATED WORKS

Control the Parameterization

- Aigerman et al. 2015
- Kovalsky et al. 2016
- Myles and Zorin 2013
- Purnomo et al. 2004
- Ray et al. 2010

Modify Rendering Pipeline

- Toth 2013
- Piponi and Borshukov 2000

Avoid Parameterization

- Yuksel et al. 2010
RELATED WORKS

Control the Parameterization

- [Aigerman et al. 2015]
- [Kovalsky et al. 2016]
- [Myles and Zorin 2013]
- [Purnomo et al. 2004]
- [Ray et al. 2010]

Modify Rendering Pipeline

- [Toth 2013]
- [Piponi and Borshukov 2000]

Avoid Parameterization

- [Yuksel et al. 2010]

Optimize Texture Values

- [Iwanicki 2013]
VALUE ALONG AN EDGE
VALUE ALONG AN EDGE
VALUE ALONG AN EDGE
VALUE ALONG AN EDGE
BILINEAR INTERPOLATION

Bilinear interpolation:

\[ \text{Bilerp}(s, t) = (1 - t)((p_{10} - p_{00})s + p_{00}) + t((p_{11} - p_{01})s + p_{01}) \]
BILINEAR INTERPOLATION

Bilinear interpolation:

\[ \text{Bilerp}(s, t) = (1 - t)((p_{10} - p_{00})s + p_{00}) + t((p_{11} - p_{01})s + p_{01}) \]

This is linear in \( p \) and quadratic in edge parameter \( \gamma \):

\[ \text{Bilerp}(e) = m(e(\gamma))p \]
BILINEAR INTERPOLATION

Bilinear interpolation:

\[ \text{Bilerp}(s, t) = (1 - t)((p_{10} - p_{00})s + p_{00}) + t((p_{11} - p_{01})s + p_{01}) \]

This is linear in $p$ and quadratic in edge parameter $\gamma$:

\[ \text{Bilerp}(e) = m(e(\gamma))p = \gamma^2 \cdot a(\gamma)^T p + \gamma \cdot b(\gamma)^T p + c(\gamma)^T p \]
BILINEAR INTERPOLATION

Bilinear interpolation:

\[ \text{Bilerp}(s, t) = (1 - t)((p_{10} - p_{00})s + p_{00}) + t((p_{11} - p_{01})s + p_{01}) \]

This is linear in \( p \) and quadratic in edge parameter \( \gamma \):

\[ \text{Bilerp}(e) = m(e(\gamma))p = \gamma^2 \cdot a(\gamma)^T p + \gamma \cdot b(\gamma)^T p + c(\gamma)^T p \]

\( \gamma \in [0, 1] \), \( a, b, c \) are sparse column vectors of coefficients for \( e \), and \( p \) is the column vector of all samples in the texture.
SEAM ENERGY

\[
\int_0^1 \| m(e_1)p - m(e_2)p \|^2 d\gamma
\]
SEAM ENERGY

\[ p^T \left( \int_0^1 \| m(e_1) - m(e_2) \|^2 d\gamma \right) p \]
SEAM ENERGY

\[ p^T \begin{pmatrix} M_{e_1,e_2} \end{pmatrix} p \]
SEAM ENERGY

\[ p^T M p = \sum_{e_1, e_2 \in \text{seams}} p^T \begin{pmatrix} M_{e_1, e_2} \\ \end{pmatrix} p \]
POSSIBLE SOLUTIONS

\[ p^T M p = 0 \]
POSSIBLE SOLUTIONS
OPTIMIZATION

Our total energy is:

\[ E(p) = \]
OPTIMIZATION

Our total energy is:

\[ E(p) = w_{\text{change}} \| p - p_0 \|^2 \]
OPTIMIZATION

Our total energy is:

\[ E(p) = w_{\text{change}} \| p - p_0 \|^2 \]
OPTIMIZATION

Our total energy is:

\[ E(p) = w_{\text{change}} \| p - p_0 \|^2 + w_{\nabla} \| \nabla p - \nabla p_0 \|^2 \]
OPTIMIZATION

Our total energy is:

\[ E(p) = w_{\text{change}} \| p - p_0 \|^2 + w_{\nabla} \| \nabla p - \nabla p_0 \|^2 \]
OPTIMIZATION

Our total energy is:

\[ E(p) = w_{\text{change}} \| p - p_0 \|^2 + w_{\nabla} \| \nabla p - \nabla p_0 \|^2 \]
Our total energy is:

\[ E(p) = w_{\text{change}} \| p - p_0 \|^2 + w_{\nabla} \| \nabla p - \nabla p_0 \|^2 \]
OPTIMIZATION

Our total energy is:

\[ E(p) = w_{\text{change}} \| p - p_0 \|^2 + w_{\nabla} \| \nabla p - \nabla p_0 \|^2 + w_{C^1} E_{C^1}(p) \]
OPTIMIZATION

Our total energy is:

\[ E(p) = w_{\text{change}} \left\| p - p_0 \right\|^2 + w_\nabla \left\| \nabla p - \nabla p_0 \right\|^2 + w_{C^1} E_{C^1}(p) \]
Our total energy is:

\[
E(p) = w_{\text{change}} \left\| p - p_0 \right\|^2 + w_\nabla \left\| \nabla p - \nabla p_0 \right\|^2 + w_{C^1} E_{C^1}(p)
\]
OPTIMIZATION

Our total energy is:

$$E(p) = w_{\text{change}} \| p - p_0 \|^2 + w_{\nabla} \| \nabla p - \nabla p_0 \|^2 + w_{C^1} E_{C^1}(p)$$

Subject to

$$E_{\text{seam}}(p) = p^T M p = 0$$
OPTIMIZATION

Our total energy is:

\[ E(p) = w_{\text{change}} \| p - p_0 \|^2 + w_\nabla \| \nabla p - \nabla p_0 \|^2 + w_{C^1} E_{C^1}(p) \]

Subject to \( E_{\text{seam}}(p) = p^T M p = 0 \)

We impose the null space constraint via the penalty method by adding:

\[ w_{\text{seam}} E_{\text{seam}}(p) \]
Our total energy is:

\[ E(p) = w_{\text{change}} \| p - p_0 \|^2_{} + w_{\nabla} \| \nabla p - \nabla p_0 \|^2_{\text{ }} + w_{C^1} E_{C^1}(p) \]

Subject to \[ E_{\text{seam}}(p) = p^T M p = 0 \]

We impose the null space constraint via the penalty method by adding:

\[ w_{\text{seam}} E_{\text{seam}}(p) \]

with weights

\[ w_{\text{seam}} \gg w_{\text{change}}, w_{\nabla}, w_{C^1} \]
Seam Erasure: Results
COLOR MAP

Before

After
COLOR MAP

Before

After
NORMAL MAP

Before

After
NORMAL MAP

Before

After
NORMAL MAP

Before

After
CONTRIBUTIONS

Seam Erasure

Seam Straightener

Seam Aware Decimation

Weight Texture Maps
CONTRIBUTIONS

Seam Erasure

Seam Straightener

Seam Aware Decimation

Weight Texture Maps
Seamless

Liu, Ferguson, Jacobson and Gingold

GARLAND AND HECKBERT [1998]
GARLAND AND HECKBERT [1998]
MAYA DECIMATION
OUR APPROACH
GREEDY EDGE COLLAPSE

Based on Garland and Heckbert [1998]’s n-D Quadric Error Metric
GREEDY EDGE COLLAPSE

Based on Garland and Heckbert [1998]’s n-D Quadric Error Metric
GREEDY EDGE COLLAPSE

Based on Garland and Heckbert [1998]'s n-D Quadric Error Metric
GREEDY EDGE COLLAPSE

Based on Garland and Heckbert [1998]’s n-D Quadric Error Metric

- Each face defines a plane (e.g. 5-D for \([x, y, z, u, v]\))
GREEDY EDGE COLLAPSE

Based on Garland and Heckbert [1998]’s n-D Quadric Error Metric

- Each face defines a plane (e.g. 5-D for \([x, y, z, u, v]\))
- Edge error metric = sum of squared distances to face's planes
GREEDY EDGE COLLAPSE

Based on Garland and Heckbert [1998]’s n-D Quadric Error Metric

- Each face defines a plane (e.g. 5-D for [x, y, z, u, v])
- Edge error metric = sum of squared distances to face's planes
- New vertex position minimizes the edge error metric and keeps the edge error metric.
LENGTH RATIO CRITERIA

\[ e_1, e_2, f_1, f_2 \]
LENGTH RATIO CRITERIA
LENGTH RATIO CRITERIA

- Merging $e_1 f_1$ and $e_2 f_2$ will cause the stripe texture to be misaligned across the seam.
- Length Ratio Criteria:

$$\frac{\|e_1\|}{\|f_1\|} = \frac{\|e_2\|}{\|f_2\|}$$
LINK CONDITION
TWO UNIFIABLE EDGES
THREE UNIFIABLE EDGES

d_1  e_1  f_1

d_2  e_2  f_2

(c)
Seam Aware Decimation: Results
DECIMATION RESULT
DECIMATION RESULT

Mesh

Parameterization

100%

3%
CONTRIBUTIONS

Seam Erasure

Seam Aware Decimation

Seam Straightener

Weight Maps
CONTRIBUTIONS

Seam Erasure

Seam Aware Decimation

Seam Straightener

Weight Maps
SEAM STRAIGHTENER
SEAM STRAIGHTENER
EDGE COMPONENT STRAIGHTENING
EDGE COMPONENT STRAIGHTENING

“4D” non-straight seam
EDGE COMPONENT STRAIGHTENING

“4D” non-straight seam

“4D” straightened seam
EDGE COMPONENT STRAIGHTENING

"4D" non-straight seam

"4D" straightened seam
SEAM STRAIGHTENING RESULTS

![Graph showing accumulated cost vs. decimation percentage with different tolerance levels.](image)

- Tolerance:
  - Blue: No straightening
  - Green: 0.0001
  - Orange: 0.001
  - Yellow: 0.01
  - Purple: 0.1
## UN-COLLAPSIBLE EDGES

<table>
<thead>
<tr>
<th>Example</th>
<th># Un-Collapsible Edges Before</th>
<th># Un-Collapsible Edges After</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chimp</td>
<td>805</td>
<td>171</td>
</tr>
<tr>
<td>Hercules</td>
<td>626</td>
<td>290</td>
</tr>
<tr>
<td>Animal</td>
<td>369</td>
<td>17</td>
</tr>
<tr>
<td>Wolf</td>
<td>374</td>
<td>173</td>
</tr>
</tbody>
</table>
## UN-COLLABSIBLE EDGES

<table>
<thead>
<tr>
<th>Example</th>
<th># Un-Collapsible Edges Before</th>
<th># Un-Collapsible Edges After</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chimp</td>
<td>805</td>
<td>171</td>
</tr>
<tr>
<td>Hercules</td>
<td>626</td>
<td>290</td>
</tr>
<tr>
<td>Animal</td>
<td>369</td>
<td>17</td>
</tr>
<tr>
<td>Wolf</td>
<td>374</td>
<td>173</td>
</tr>
</tbody>
</table>
CONTRIBUTIONS

Seam Erasure

Seam Aware Decimation

Seam Straightener

Weight Maps
CONTRIBUTIONS

Seam Erasure

Seam Straightener

Seam Aware Decimation

Weight Maps
PER-VERTEX SKINNING
PER-VERTEX SKINNING

$\mathbf{v}_i$ Undeformed

$\mathbf{v}_j$

midpoint
PER-VERTEX SKINNING

Low resolution weights
PER-VERTEX SKINNING

High resolution weights

Low resolution weights

$\mathbf{v}_i$ Undeformed

$\mathbf{v}_j$
SKINNING WITH HIGH-RESOLUTION WEIGHTS
SKINNING WITH HIGH-RESOLUTION WEIGHTS
MODERN GPU PIPELINE
MODERN GPU PIPELINE

- Vertex Shader
- Tessellation Shader
- Fragment Shader
WEIGHTS MAP AS TEXTURES
WEIGHTS MAP AS TEXTURES
SKIN COMPLICATED MODEL WITH WEIGHT TEXTURES
SKIN COMPLICATED MODEL WITH WEIGHT TEXTURES
DEFORMATION WITH WEIGHT MAPS

Original  Decimated  Tessellated  Deformed
DEFORMATION WITH WEIGHT MAPS

Original  Decimated  Tessellated  Deformed
DEFORMATION WITH WEIGHT MAPS

Original  Decimated  Tessellated  Deformed
DEFORMATION WITH WEIGHT MAPS

Original

Decimated

Tessellated

Deformed
RESOLUTION OF WEIGHT MAPS

1024x1024  64x64  16x16  4x4
WEIGHT PAINTING
WEIGHT PAINTING
WEIGHT PAINTING
DUAL QUATERNION SKINNING WITH WEIGHT MAPS

Bend
Per-Vertex DQS

High-resolution DQS

Twist

Bend & Twist
FREE-FORM DEFORMATION WITH WEIGHT MAPS
CONCLUSION
CONCLUSION

Seam Erasure
CONCLUSION

Seam Erasure

Seam Aware Decimation
CONCLUSION

Seam Erasure

Seam Straightener

Seam Aware Decimation
CONCLUSION

Seam Erasure

Seam Straightener

Seam Aware Decimation

Weight Maps
LIMITATIONS AND FUTURE WORK

• Limitations:
  • Low resolution result is constant
  • Non-overlapping parametrization
  • Tangent space normal maps

• Future Work:
  • Minimize the bilinear reconstruction error of the displacement and geometry images
  • Volumetric textures (trilinear interpolation)
SEAMLESS: SEAM ERASURE AND SEAM-AWARE DECOUPLING OF SHAPE FROM MESH RESOLUTION

Project page and Source code: https://cragl.cs.gmu.edu/seamless/

Contact:
Zachary Ferguson, zfergus@nyu.edu
Songrun Liu, sliu11@gmu.edu

We are grateful to Guilin Liu and Jyh-Ming Lien, Keenan Crane, and Turbosquid users Sumatra3d, Deniz Ozemre, SpinQuad1976, Pabong, Tornado Studio, and mnphmmn.

This work was supported by the US NSF, Google, NSERC, and Adobe Systems Inc.