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

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Thank you for the introduction.
I will be presenting the entire paper as my co-author, Songrun Liu, could not make it today.
Textures are ubiquitous in computer graphics. They can be used to apply color to a surface, normals of a surface, displacement of the surface, and even the 3D positions of the entire surface, as Gu et al. showed with geometry images in 2002.
TEXTURE MAPPING

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Our goal is therefore to remove these seam discontinuities <click>. 

SEAM DISCONTINUITIES
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We present four novel techniques to solve the problem of seams. First, we present our seam erasure which erases seam artifacts from texture images. Second, we introduce a seam aware decimation in which we can decimate our model, collapsing surface elements, while reusing the same texture. Third, we introduce a seam straightening algorithm to better assist our decimations. Lastly, we show how skinning weights can be stored in textures to adaptively tessellate and deform a model. Let us start with the seam erasure.
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CONTRIBUTIONS

Seam Erasure

Seam Aware Decimation

Seam Straightener

Weight Maps

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Our algorithm takes as input a 3D model with a 2D parameterization and a texture image. We then output a texture with the seam erased. This is a one-time preprocess and requires no additional runtime cost.
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Previous attempts have been made to fix the problem of seams. Some control the parameterization. Others modify the rendering pipeline, and some avoid parameterization altogether. Our work is orthogonal to the choice of the original parameterization and stands to make this family of work more useful. The closest approach to ours was developed in industry and briefly described by Iwanicki [2013], who also optimize texture values.

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BILINEAR INTERPOLATION

Bilinear interpolation:

\[ \text{Bilerp}(s, t) = (1 - t)((p_{10} - p_{00})s + p_{00}) + t((p_{11} - p_{01})s + p_{01}) \]
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\[ \text{Bilerp}(\epsilon) = m(\epsilon(\gamma))p = \gamma^2 \cdot a(\gamma)^T p + \gamma \cdot b(\gamma)^T p + c(\gamma)^T p \]

\( \gamma \in [0, 1] \), \( a, b, c \) are sparse column vectors of coefficients for \( \epsilon \), and \( p \) is the column vector of all samples in the texture.
We integrate the squared difference of edge values. The edge value is linear in \( p \) is independent of gamma, so we can pull it out. The integral can be analytically integrated to be a square matrix. We then sum over all edge pairs to produce our final seam energy. This energy is quadratic in \( p \).
SEAM ENERGY

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

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\[ p^\top \begin{pmatrix} M_{e_1,e_2} \\ \cdot \end{pmatrix} p \]
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$$p^T M p = \sum_{e_1, e_2 \in \text{seams}} p^T \left( \begin{array}{cc} M_{e_1, e_2} & \end{array} \right) p$$
POSSIBLE SOLUTIONS

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OPTIMIZATION

Our total energy is:

\[ E(p) = \]

In order to choose a solution we introduce a set of regulatory energies. We use a least squares approach to express the reliability of interior twels. This however preserves the outside values too exactly, resulting in poor interpolation. Therefore, we add a gradient domain term to allow for global effects resulting from enforcing seam continuity. As this animation plays the gradient weight increases.

For smoothness, we introduce an energy term that measures the integrated \( C^1 \) discontinuity across seams. This is implemented similarly to the seam energy.

We optimize this energy subject to being in the null space of the seam energy. A weighted term for the seam. Where \( w_\text{seam} \) much larger then all other weights.
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Let us see some results of the seam erasure.
Here the texture values define the surface color. See how the color changes sharply across the seam. After the seam erasure, the edges agree on a smoothed value.
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COLOR MAP

Before  After

Here the texture values define the surface color. (click) See how the color changes sharply across the seam. (click) After the seam erasure, the edges agree on a smoothed value.
Here the seam is visible when defining surface normals in the texture. <click> Notice how artists place seams in hard to see areas. For example on the belly of this cow model. Hiding seams takes great deal of effort. <click> Our research stands to fix this process by erasing the seams independent of where it is placed.
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CONTRIBUTIONS

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Seam Aware Decimation

Seam Straightener

Weight Texture Maps

We have now fixed the problem of seams in textures, but if we want to reuse these textures on varying level of detail models, we may introduce seams. All of our work erasing the seam would have to be done over again. To avoid this we implement a seam aware decimation that will prevent seam artifacts arising from decimation.
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To best understand our approach, let us compare the decimation results of others. We want to decimate this dense fish model. Seams of the model are drawn in magenta.
Garland and Heckbert [1998] (implemented by MeshLab [Cignoni et al. 2008]) do not preserve seams precisely, leading to artifacts in the texture. Red areas near seams in the inset parameterization indicate this deviation in the parametric domain.
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Maya [2017] prevents decimation of seams entirely, leading to suboptimal allocation of mesh vertices.
Our seamless decimation allows the same texture to be used across all decimation levels—notably along seams. Given a seam-free textures, we describe criteria that must be satisfied to be able to collapse an edge without introducing a discontinuity, and conditions that the new vertex’s uv parametric coordinates must satisfy.
GREEDY EDGE COLLAPSE

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

We base our seam aware decimation on Garland and Heckbert's n-D Quadric Error Metric. Edges are collapsed greedily according to the quadric error metric. This algorithm may cause seams discontinuities, so we introduce additional criteria to prevent them.
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- 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.
Preserving only the uv shape of seams can still introduce discontinuities due to mismatched sampling. In this example, <read point 1>. <click> To avoid this scenario we implement a length ratio criteria. <click>
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Length Ratio Criteria:

\[ \frac{\| e_1 \|}{\| f_1 \|} = \frac{\| e_2 \|}{\| f_2 \|} \]
To prevent changes in the topology of the mesh we, implement a link condition. That is, we prevent collapsing a non-seam edges whose endpoints are both on the seam.
In this example e and f are unifiable because they are collinear and satisfy the length ratio condition. However, e and d cannot be unified because they are not collinear. Therefore, when collapsing e, the only satisfying new vertex placement in uv is for endpoints to move to the location of the red vertices.
In this example, e, f, and d are unifiable, so both endpoints of e1 and e2 are free to move. The new vertex placement in uv and xyz will be determined by minimizing the quadric metric subject to collinearity constraints.
Let us see some results of our decimation algorithm.
Here, this animal model is heavily decimated to 3% of its original edges. In the parameterization, the seam boundary shape is preserved.
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This Hercules model is decimated using our algorithm. Watch as edges are collapsed until tessellation. We can now adaptively tessellate the surface reusing the same texture.
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Our original vertices are illustrated here with mismatched edge length ratios. <click> We treat this as a 4D curve, show here in the 2D, the dimensions are [u, x, u′, v′]. <click> We straighten the curve using iterative Ramer-Douglas-Peucker method. <click> Because we straighten according to arc-length, the edge-length ratios match.

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Two halves of a seam with original vertices \{a, b, c, d, e\} and \{a′, b′, c′, d′, e′\} are illustrated as black chains with mismatching edge length ratios (left and top). We straighten the seam, treating it as a 4D curve (illustrated here as a black 2D curve reduced to a red curve). The vertices are repositioned along the curve in 4D, and these define the parametric vertex positions along the original seams (right and bottom). Because their parametrizations agree, edge-length ratios now also agree.
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Two halves of a seam with original vertices \{a, b, c, d, e\} and \{a', b', c', d', e'\} are illustrated as black chains with mismatching edge length ratios (left and top). We straighten the seam, treating it as a 4D curve (illustrated here as a black 2D curve reduced to a red curve). The vertices are repositioned along the curve in 4D, and these define the parametric vertex positions along the original seams (right and bottom). Because their parametrizations agree, edge-length ratios now also agree.
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Two halves of a seam with original vertices \([a, b, c, d, e]\) and \([a', b', c', d', e']\) are illustrated as black chains with mismatching edge length ratios (left and top). We straighten the seam, treating it as a 4D curve (illustrated here as a black 2D curve reduced to a red curve). The vertices are repositioned along the curve in 4D, and these define the parametric vertex positions along the original seams (right and bottom). Because their parametrizations agree, edge-length ratios now also agree.
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SEAM STRAIGHTENING RESULTS

The accumulated metric cost of edge collapses to decimate a model (stick) decreases as more straightening is performed. Each curve represents a different straightening tolerance. Straightening increases the number of seam edges that can be collapsed, allowing for a more effective use of the mesh resolution and therefore a lower total error.
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>

Here we can see the number of un-collapsible edges before straightening. After straightening this number decreases.
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In total, we have erased the seam from texture and designed a decimation algorithm that allows texture reuse. We can combine both of these techniques to aid deformation of 3D models by storing skinning weights in a texture image and sending a minimal number of triangles to the GPU.
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Linear blend skinning weights are stored per-vertex; a mesh is deformed by deforming its vertices. As a result, triangles stay triangles and edges between vertices stay straight.
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For models with a lot of bones, we can easily pack multiple textures into one to save the resource of texture units, which is often limited by the hardware.
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We are able to get complex poses without seams for as small as 16 x 16 textures. Smaller textures result in a constant function in order to preserve the seam continuity.
WEIGHT PAINTING
WEIGHT PAINTING
WEIGHT PAINTING
Our approach can be extended to other skinning approaches such as Dual quaternion skinning and <click>
FREE-FORM DEFORMATION WITH WEIGHT MAPS

free-form deformation.
CONCLUSION

In total we have erased the seam from our textures in a one-time preprocess. This does not change the rendering pipeline and therefore can be easily integrated in current workflows. We also showed how we can decimate a model without introducing seam artifacts. This allows models with the same parametric domain to share texture images. To aid in our decimation we introduced a seam straightening algorithm. Increasing the number of collinear seam edges and therefore the quality of decimation. Lastly, we combined our seamless texture and decimated models to show how skinning weights for deformations can be stored in textures and adaptively used to create weight maps.
CONCLUSION

Seam Erasure

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CONCLUSION

Seam Erasure

Seam Aware Decimation

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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/

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The source code is currently accessible online, and if you have any questions in the future feel free to contact either Songrun or myself.