Generalized Haptic Relief Atlas for Rendering Surface Detail

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Abstract: A fast global approach that encodes haptic surface relief detail using an image-based Hybrid Rugosity Mesostructure Atlas (HyRMA) shell is presented. It is based on a depth/normal texture computed from surface differences of the same mesh object at different resolutions (a dense one with thousands/millions of triangles, and a highly decimated version). Per-face local depth differences are *warped* from volume space into tangent space, and stored in a sorted relief atlas. Next, the atlas is sampled by a vertex/fragment shader pair, *unwarped*, displacing the pixels at each face of the decimated mesh to render the original mesh detail with quite fewer triangles. We achieve accurate correspondence between visualization of surface detail and perception of its fine features without compromising rendering framerates, with some loss of detail at mesostructure "holes".

1 INTRODUCTION

Haptic rendering of complex models requires high frequency feedback of collision forces. Visually rendering highly detailed objects at the same time effectively reduces haptic sampling rates and therefore touch perception. We present a solution for fast visualization using an image-based haptic atlas of *per face* displacement textures and corresponding normalmaps in substitution of actual geometry. The procedure grows as a generalization of a haptic rendering acceleration method based on rugosity mesostructures, modified for synced visualization of relief detail.

The approach is a two-step procedure encoding all relief detail using an image-based Hybrid Rugosity Mesostructure Atlas (HyRMA) shell, capturing the surface detail of a dense mesh from depth differences against piecewise triangular prism volumes extruded from the triangles of a highly decimated version of the same mesh, and then warping all depth information into orthogonal triangular prisms. Warped depths and *unwarped* normals are stored as a non-contiguous RGBα texture atlas in tangent space. In the rendering step, this tangent-based atlas is sampled in a relief shader applied to the decimated mesh, rendering the original surface relief with quite fewer triangles.

The contribution of this global approach is that accurate correspondence between the surface detail rendering and fine features' perception is achieved without compromising rendering framerates, ensuring G^0 and G^1 geometric continuity among faces, and a qualification of loss of detail for cavities in mesostructures

The article is organized as follows: in section 2 we present a review of pertinent work in image-based relief rendering. Section 3 describes how to build tangent-space relief atlases out of meshes. Section 4 explains how to use the atlases for relief generation using a GPU shader. Section 5 presents the results from test meshes and mesostructures, ending with conclusions towards optimizing mesostructure rendering of large meshes.

2 PREVIOUS WORK

Next we review relevant milestones relevant for understanding the context of this work. A good survey for spatial deformation methods is presented in (Gain and Bechmann, 2008), describing a family of modelling techniques for indirectly reshaping objects, interactively warping the surrounding space and applicable to a variety of object representations.

Texture Atlases Approaches

There have been few insights of the problems surrounding the use of heightfield displacements for image-based rendering, such as concave areas and holes, the emphasis being made in texture stitching. Levy *et al* (Lévy et al., 2002) describes the Texture

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Atlas method of mapping surfaces in an optimal one-to-one correspondence of texture and geometry along contour lines. Carr (Carr and Hart, 2002) describe a one-to-one mapping from an object's surface into its texture space. The method uses the graphics hardware to rasterize texture directly into the atlas. In (González and Patow, 2009) spatial discontinuities of multi-chart parameterizations are solved by a bidirectional mapping between areas outside and inside the charts, and stitching triangles by linear interpolation of texel values, at low computational cost and small memory footprint.

Pixel-based Relief Rendering

Displacement mapping approaches subdivide the original geometry into more triangles, which are displaced according to a 2D height map. A complete survey on displacement mapping algorithms can be found in (Szirmay-Kalos and Umenhoffer, 2008). These approaches rely on iterated ray casting within modern shader architectures to implement per-pixel interception, impostor representation, multisampling of depth relief and normal textures, and correct silhouette calculations for rendering geometric detail.

Hirche *et al* (Hirche et al., 2004) devise sampling a displacement map per pixel in a shader. Triangles of the base mesh are extruded along its normals and the resulting prisms are rendered by casting intersecting rays with the displaced surface. In Policarpo (Policarpo et al., 2005) a purely image-based approach uses front and back depth textures for real-time relief mapping of arbitrary polygonal surfaces. Baboud & Décoret (Baboud and Décoret, 2006) extend the former approach using six relief impostors, corresponding to faces of the object's bounding cuboid.

Parallax Occlusion Mapping (POM), described by (Tatarchuk, 2006; Dachsbacher and Tatarchuk, 2007), is a simpler procedure based on a linear search in texture space, shifting the texture coordinates along the view ray direction according to depth values, and skipping self-occluded pixels in the current view direction. The displaced surface is a prism volume, bounded by top, bottom and three slabs along the vertices' normals. Ray marching heights gradients are computed per tetrahedron (3 per prism).

A successful approach for relief mapping with correct silhouettes uses a fragment shader based on *relaxed cone step mapping*, as implemented by (Policarpo and Oliveira., 2007), which uses an additional precomputed "cone map" for mesostructure generation. Cones represent empty space between relief crests that can be safely skipped in the ray-casting process, accelerating geometry generation.

A different approach that also takes into consideration self-occlusion and self shadows is described in (Timonen and JanWesterholm, 2010), applicable only for planar heightfields. Heightfield visibility is determined as an exact horizon for a set of azimuthal directions. Surface is shaded using the horizon information with the light environment, producing detailed shadows. Finally, Theoktisto (Theoktisto et al., 2010) describes a method to displace a triangle mesh using an haptic Rugosity Mesostructure (HyRMA) built from depth differences and normal maps.

3 TANGENT-SPACE RELIEF ATLAS GENERATION

The proposed global rendering method extends the procedure described by Theoktisto for displacing a triangle mesh with an image-based rugosity mesostructure applied in haptic rendering.

The Rugosity Mesostructure

The Hybrid Rugosity Mesostructure or HyRMA is an extensible "skin shell" set atop a triangle. A dense mesh is represented by a much simpler decimated mesh, while the missing relief is provided by piecewise triangular chunks composed of heightfield displacements, normalmaps and other information placed on top of each triangle. It encodes all geometric information needed for haptic interaction as 2D textures in four or more channels. The first 3 channels store a normalmap representing surface normals while its heightfield displacement is stored in the 4^{th} channel.

3.1 Per-face Normal-depth Atlases

The local nature of the previous approach allows loading arbitrary and unrelated displacement textures and normals on top of a coarse mesh, requiring a special treatment of edge bands when crossing triangles' edges. Typically a vertex is ancillary to an average of 6 faces, all of them participating in the blending. This gets very cumbersome for large number of triangles.

We now present a global method to produce a continuous atlas (in tangent space) of hybrid rugosity mesostructures, or HyRMAs, capturing geometric information from a dense mesh into a multichannel texture, which is then used as a "shell" layered onto a simpler mesh (highly decimated from the former) with all major features preserved to render as much as possible surface detail.

This decimation is obtained by a Quadric Edge Collapse Decimation algorithm (Hoppe, 1999; Tarini

et al., 2010) for feature preserving polygon reduction, as implemented in the MeshLab software (Visual Computing Lab, ISTI–CNR, Pisa, Italy, 2012). Mesh construction and operations are handled using the Trimesh2 C++ library from Princeton ImageX Labs (Rusinkiewicz, 2012).

Local Relief Volume Warp

A preprocessing step is necessary to obtain a high resolution HyRMA "shell" from the M_F mesh, and then obtain a decimated mesh from it. This mesh M_s need not be optimal in size, needing only to preserve all relevant major surface features (ridges, holes, bumps and depressions) within some error metric. Mesh M_s and the haptic HyRMA atlas will provide all the necessary visual information.

The volumes H and H' (the triangular wedge built around triangle *i* of the simplified mesh, and its corresponding orthogonal prism) map to each other parametrically in normalized barycentric coordinates (α, β, γ) throughout trilinear interpolation.

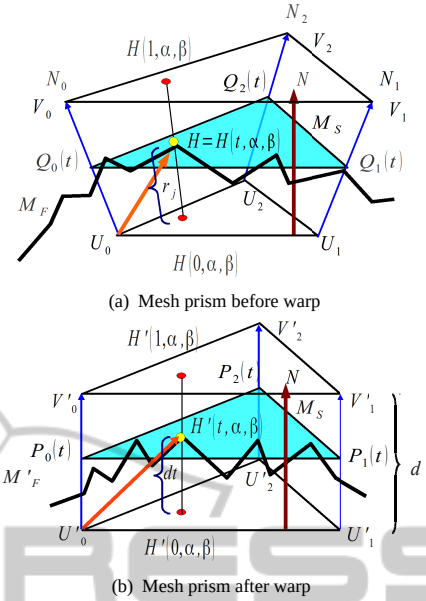
Both meshes are loaded and placed congruently (same size, origin and orientation). A prism is grown at each face of the M_s mesh alongside vertices' normals (both up and down), as shown on Figure 1. This will *triple* the number of vertices of the mesh, and *multiply by 9* the number of triangular faces. Each face f of the mesh M_s is traversed (order is irrelevant), placing a camera a constant distance d from the center of face f and orthogonal to it.

Values α and β (and $\gamma = 1-\alpha-\beta$) are barycentric coordinates, and $H(t,\alpha,\beta) = H'(t,\alpha,\beta)$ the height value corresponding to these texture coordinates. At this point, coordinates are transformed to the local space of wedge *i*, following the transformation T_i to an orthogonal prism onto the corresponding triangle at the atlas (see Figure 1) and the heightfield channel at that point is sampled.

The distance d is pre-computed by a binary search of the minimum wedge height value ensuring that the whole surface geometry will be enclosed by all wedges. Prism corners V_j and U_j are computed from vertex Q_j, displaced a perpendicular distance $\pm d/2$ along the face normal, equivalent to some value r_j along each vertex normal N_j, as shown by Equation 1.

$$\begin{aligned} Q_j(t) &= U_j + t(V_j - U_j), \quad & Q_j(t) &= U_j + t(r_j N_j) \\ P_j(t) &= U'_j + t(V'_j - U'_j), \quad & P_j(t) &= U'_j + t(dN) \\ j &= 0,1,2,\ldots & t &= \frac{\overline{U_0 H} \cdot N}{\overline{U_0 V_0} \cdot N} \end{aligned} \tag{1}$$

Vertices V_k from the M_F mesh that fall within the face prism are tagged and warped onto the corresponding orthogonal wedge by means of an (invertible) transformation T_i, a trilinear interpolation to obtain the transformed vertices V'_k.



(a) Mesh prism before warp

(b) Mesh prism after warp

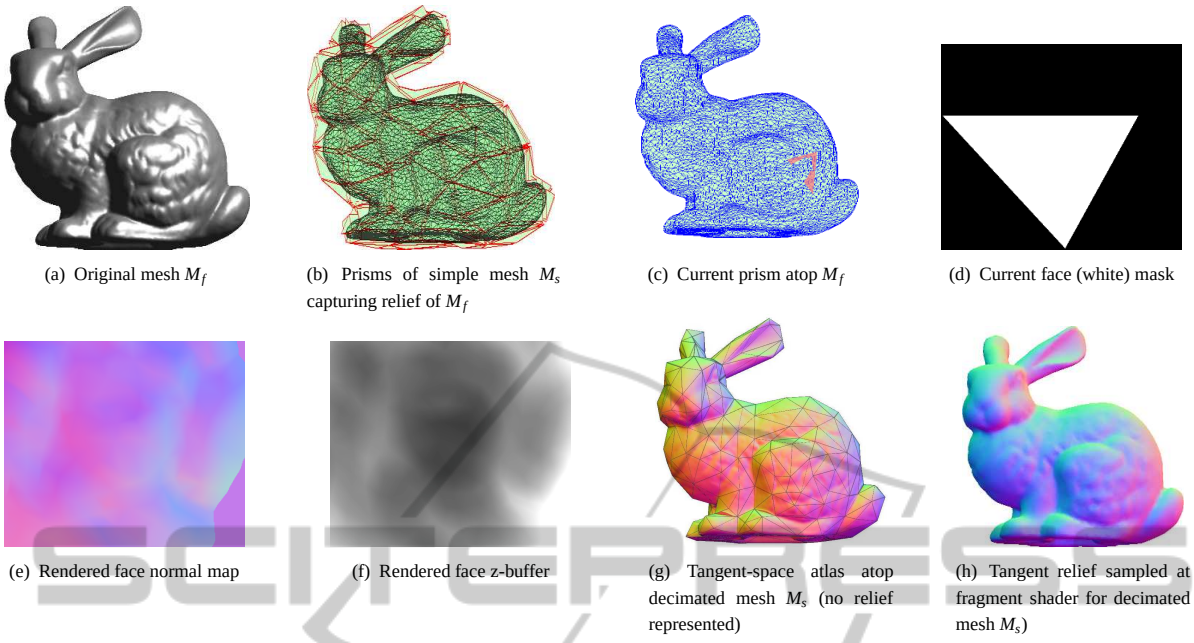
Figure 1: Heightfield Displacement Computation: Transformation T_i warps all vertices V_k's in M_F that are within the face's prism to the orthogonal prism

To obtain the relative base height of V_k, we project the distance vector from this vertex to one of the vertices of the simpler mesh M_s against the face normal. The magnitude t of the projected vector will be the relative height. Original vertex coordinates are recovered by applying T_i^{-1} to the transformed vertex V'_k.

$$\begin{aligned} H(t,\alpha,\beta) &= \alpha Q_1(t) + \beta Q_2(t) + \gamma Q_0(t) \\ H'(t,\alpha,\beta) &= \alpha P_1(t) + \beta P_2(t) + \gamma P_0(t) \end{aligned} \tag{2}$$

$$\begin{aligned} H(t,\alpha,\beta) &= \alpha[Q_1(t) - Q_0(t)] + \beta[Q_2(t) - Q_0(t)] + Q_0(t) \\ H'(t,\alpha,\beta) &= \alpha[P_1(t) - P_0(t)] + \beta[P_2(t) - P_0(t)] + P_0(t) \\ 1 &= \alpha + \beta + \gamma, \quad \text{with } \alpha,\beta,\gamma,t \in \mathbb{R}[0..1] \end{aligned}$$

To obtain the barycentric coordinates used to sample the texture, the prism is orthogonalized, warping the volume enclosed along the vertex normals (H) into a regular triangular prism with vertex normals parallel to the face normal (H'), as shown on Equation 2 Given t^*, having $\gamma = 1-\alpha-\beta$, and knowing triangle vertices $\{Q'_k s, P'_k s\}$, we have all the information needed to compute the T_i mapping. Notice that $Q_j(0.5) = P_j(0.5)$, since they are vertices from the same base triangle k of mesh M_s. Having both spaces H and H' parametrically equivalent, instead of solving a 16 by 15 linear system to find the 15 elements on a local warp matrix, we solve for each vertex a much simpler 2×2 linear system to obtain the $< \alpha, \beta >$ pairs. As long as triangles are non-degenerate (a feature of good decimation algorithms), it is straightforward to derive T_i^{-1}, the inverse transformation from tangent to object space.



(a) Original mesh M_f

(b) Prisms of simple mesh M_s capturing relief of M_f

(c) Current prism atop M_f

(d) Current face (white) mask

(e) Rendered face normal map

(f) Rendered face z-buffer

(g) Tangent-space atlas atop decimated mesh M_s (no relief represented)

(h) Tangent relief sampled at fragment shader for decimated mesh M_s)

Figure 2: The complete sequence for tangent atlas construction and image-based relief generation.

It follows that G^0 and G^1 continuity are guaranteed across edges, since a point on the shared edge of two adjacent faces of M_s will be mapped to the same height at both sides, and its normal will be the same. Therefore, when traversing the surface of mesh M_s, all transitions across edges will be undetectable, and will be perceived as non-abrupt continuous surface.

3.2 Generating the Relief Atlas in GPU

The resulting submesh of M_f (Figure 2(a)) is then rendered to an off-screen framebuffer using a vertex+fragment GPU shader, as seen on Figure 2(h).

Each face of M_s (Figure 2(b)) gets focused by a camera placed just outside of the top lid of the prism, and the same transformation is applied to mesh M_f. An orthonormal projection samples homogeneously the relief volume without precision loss.

Mesh M_f is then rendered from that point of view, with an overlap border of two pixels, to avoid rendering artifacts at the edge borders. All vertices belonging to M_f within the space of constructed prism (slightly grown to actually including some neighbouring outer vertices and faces to avoid special cases when triangles of the low and high resolution mesh coincide at edges or verices) are warped to the orthogonal prism, as previously explained in Figure 1.

The current face area as a stencil (Figure 2(c)), to simultaneously cut the renderings of mesh M_f to the depth buffer in the range between the two lids of the prism, (Figure 2(f)), and the corresponding normal map (Figure 2(e)). The procedure is repeated for each triangle of the M_s mesh, collecting all HyRMA pairs in the atlas one by one. To save memory and disk space, the texture triangles are sorted by edge size and stored alternately facing up and down. The corresponding *uv* coordinates are also stored in a separate text file. An example of textured triangles is shown in Figure 3, with the normalmap RGB channel (Figure 3(a)) and the relief map α channel (Figure 3(b)).

The processing part first phase of the texture generation takes enough time (several seconds) so it is not suitable for realtime generation (yet). However, after a tangent atlas has been generated (it only needs to be done once), rendering relief is quite fast.

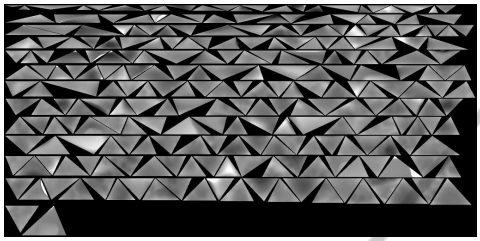
4 TANGENT-SPACE RELIEF ATLAS RENDERING

The procedure for rendering higher visual detail is straightforward: Load the lower resolution mesh M_s, the tangent-space texture atlas, the corresponding *uv* mapping coordinates, then use a vertex shader to map vertices to its correspondent *uv mapping*, prism and texture, and the modified parallax occlusion fragment shader takes the brunt of the work for relief rendering.

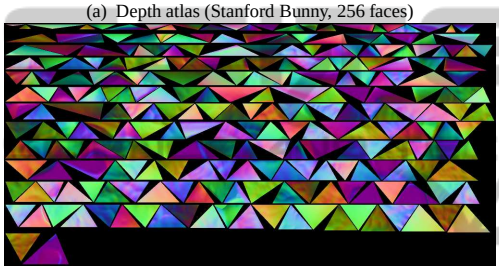
A run of the shading procedure (without relief heights, to show the underlying mesh) is shown on Figure 2(g), and the generated image with relief depth and normals calculated by the parallax occlusion shader is shown on Figure 2(h). Quality of volume de-

Table 1: Test Hi and Lo meshes.

HiRes mesh	Triangles	LoRes mesh	Triangles	RGBα Texture	Avg. FPS	Avg. POM iterations
sphere4	5,120	sphere1	80	1024×1536	645	10
sphere8	1,310,720	sphere2	320	2048×932	223	5
bunny	144,046	bunny512	512	4096×1407	226	10
bunny	144,046	bunny8192	8192	4096×2048	171	5
armadillo	32768	armadillo1024	8192	4096×8192	155	5
armadillo	345,944	armadillo16384	16384	8192×16384	92	3

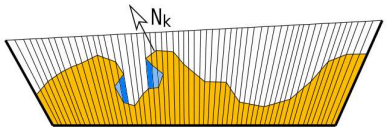


(a) Depth atlas (Stanford Bunny, 256 faces)

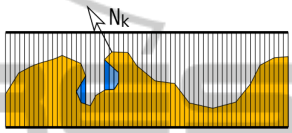


(b) Normalmap atlas (Stanford Bunny, 256 faces)

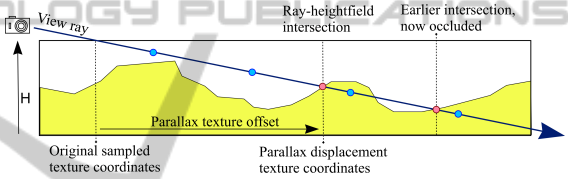
Figure 3: Tangent atlas for the Stanford Bunny, stored by edge length with alternating orientation.



(a) Before Warp: concave region (in blue) won't be included in the tangent atlas



(b) Reversing the transformation renders a modified geometry with smoothed holes



(c) A View Ray in orthogonal prism space samples the relief repeatedly in tangent space (blue circles). Two Ray intersections (in red) are shown; rightmost one is occluded

Figure 4: Tangent atlas warp.

tail depends on texture size for each rendered triangle in tangent space, and a maximum size of 256x256 or 512x512 per triangle of mesh M_s is quite adequate for quick and accurate relief rendering. The creation of a tangent atlas texture is a *lossy* transformation. As seen in Figure 4, obtaining the atlas will eliminate some concave holes, since they (Figure 4(a) will be transformed orthogonally and lose subsurface empty volume. When reconstructed, holes' walls will be along the surface interpolated normals (Figure 4(b)), having minor effects in lighting and shadow generation, depending on the decimation level.

Modified Parallax Occlusion Mapping Shader

The fragment shader has some modifications from the standard POM shader, to account for correct sampling of the atlas, as shown in Figure 4(c):

1. In the vertex shader pass, the base triangle is identified (all 1+8 triangles from the same prism share the same tag), and variables are set up for the fragment shader pass, warping the entry and exit points of the view ray crossing the prism.
2. A linear search loop samples several points back to front, from the view ray's exit point up to the prism's entry point. The sampling rate is adjusted according to the angle between the view ray and the geometric normal of the face, higher for near horizontal rays, and close to 1 in near vertical rays. If the ray's height is lower than the sampled relief height, search for the boundary along the ray (towards the camera), and find the point in which the ray hits the heightfield surface.
3. Obtain the parallax displacement, displace the pixel in tangent space, and then unwarp to obtain the real displacement.
4. Optionally, provide a loop for lights and shadows. The procedure for shadow pixels is similar, but using light rays for the calculation.

5 RESULTS

The testing equipment for the procedure is an Intel(R) Core(TM) Quad CPU Q9550 (2.83GHz, 64 bit) with a NVIDIA GeForce 9800GT (1 GB) graphics card,

having OpenGL v.3.3 – GLSL v.330. Except in the sphere models, most triangles are dissimilar, and may be represented by small pixel chunks in the map. Texture files have a maximum horizontal width of 8192 pixels, but are limitless in length. Texture size for each individual triangle is 256×256 or 512×512.

Several models where chosen: Spheres at varying resolutions (an icosehedron being the "simpler" mesh); the Stanford Bunny mesh (144,046 triangles, 72,027 vertices); the Armadillo mesh (345,944 faces, 172,974 vertices). Table 1 shows several resolutions of the meshes of each model.

There is not much difference rendering meshes with one million triangles and one of five thousand. A high number of triangles is offset by the reduced individual size of each texture and its parallax rendering. Only those triangles that are near silhouette's edges or belonging to sharp features need more iteration, since front-facing triangles will have very little parallax displacement, and the fragment shader does not spend much time iterating. This means that for each object model there is an optimal combination of high and low resolution meshes that allows rendering all geometric detail with the best performance.

Overall, using the same haptic image-based map for visually rendering meshes guarantees enough processing time for the high frequency sampling of collision detections needed for accurate force perception.

6 CONCLUSIONS

An approach using a haptic image-based relief atlas in warped tangent space, computed out of a low resolution mesh and a highly detailed is shown. The approach is geared for adequate visual surface representation when interacting with haptic detail. Savings in processing time may be dedicated to better calculate collisions against geometry, necessary for good detail perception in meshes with high polygon counts.

The procedure allows reducing this to a preprocessing step involving a low resolution mesh to compute a low distortion warped relief texture in tangent space, and a texture sampling approach in a fragment shader that produces good detail at interactive rates, unwarping the texture and producing apparente geometric relief using a modified POM shader.

Instead of parallax mapping, geometric displacement mapping may be used, to sample the texture and unwarp the resulting points to generate more points using a geometry shader. The method can be extended to multiresolution tangent atlases, generating separate *mipmap* relief textures at varying resolutions, allowing for more or less detail when zooming at the scene.

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