Hybrid Fur Rendering

Combining Volumetric Fur with Explicit Hair Strands

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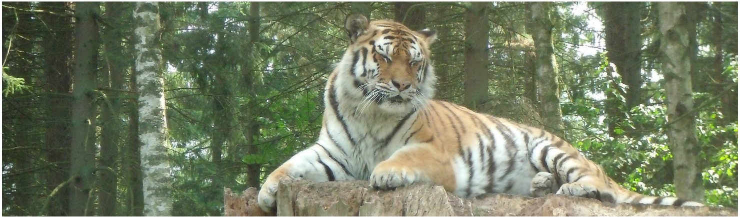
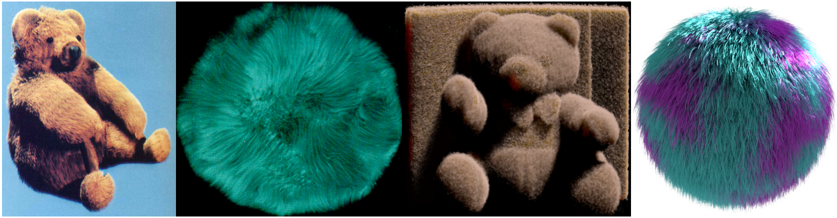
Fur density and appearance



- Animal fur is dense. A patch of 10-by-10 cm^2 easily holds more than a million hair strands (mink fur has 20k per cm^2).
- We sometimes see the individual hair strands, but we see most of the strands as a cloud of hair.
- The hair cloud has texture-like color variation and density variation resembling a smooth noise function.

Modeling implicit fur (related work)



(a) (b) (c) (d)

(a) Kajiya and Kay [1989]: ray marching a quad-based shell volume with a "cylindrical Phong model" for light scattering.

(b) Perlin and Hoffert [1989]: Noise-based fur density variation.

(c) Kniss et al. [2002]: volumetric fur with approximate multiple scattering using a regular volume instead of a shell.

(d) Heitz et al. [2015]: high-resolution microflake-based volumetric fur (as explicit fur but without aliasing problems).

(c) is interactive (frames per seconds), (d) is offline (hours per frame).

Modeling explicit fur (related work)

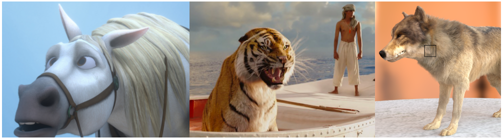
(a) explicit undercoat (a) explicit guard hairs (a) combined result

(a) Bruderlin [2003]: NURBS curves attached to follicles (surface points). Control hairs for styling. Texture maps for grooming.

(b) Sadeghi et al. [2010]: artist friendly shading.

(c) Neulander et al. [2013]: art-directable production rendering of fur qualitatively comparable to real fur.

(d) Yan et al. [2015]: physically accurate shading.



(b) (c) (d)

Rendering fur by Monte Carlo ray tracing (related work)

(a) (b) (c) (d) (d) closeup wolf fur photo

(a) Moon and Marschner [2006]: multiple scattering using photon mapping (from days to hours per frame).

(b) Moon et al. [2008]: voxelization of hairs and use of spherical harmonics for multiple scattering (hours to minutes).
Hybrid: explicit and implicit versions of the same hair strands.

(c) Zinke et al. [2008]: dual scattering with separation of local and global multiple scattering (minutes when path tracing).

(d) Yan et al. [2015]: global solution with importance-sampled physically accurate scattering model (tens of minutes).

Only (d) considers animal fur, but not the dense undercoat of real fur.

Rendering fur by rasterization (related work)

(a) (b) (c) (d) (e) (f)

(a) Lengyel [2000]: level-of-detail from explicit hairs to volumetric shell. **Hybrid: explicit and implicit versions of the same hair strands**.

(b) Lengyel et al. [2001]: storing precomputed fur appearance in textures (shells and fins) blended at runtime.

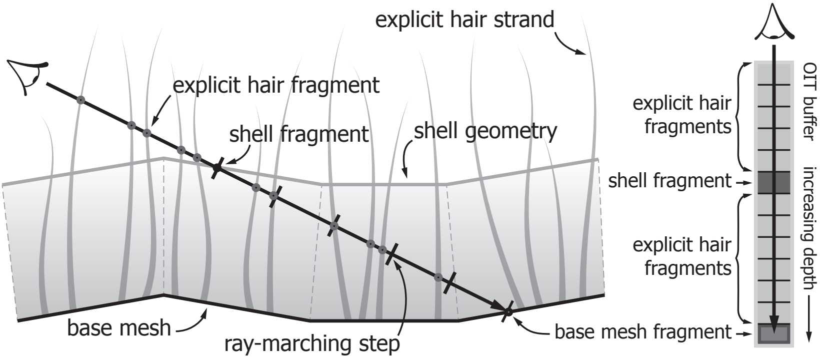
(c) Kniss et al. [2002]: slicing and blurring to render volumetric scattering using multi-pass rasterization.

(d) Zinke et al. [2008]: dual scattering approximation using deep opacity maps.

(e) Yuksel and Tariq [2010]: geometry and tesselation shaders for generating explicit hair strands.

(f) Yu et al. [2012]: order-independent transparency for accurate blending of explicit hair strands.

Hybrid fur



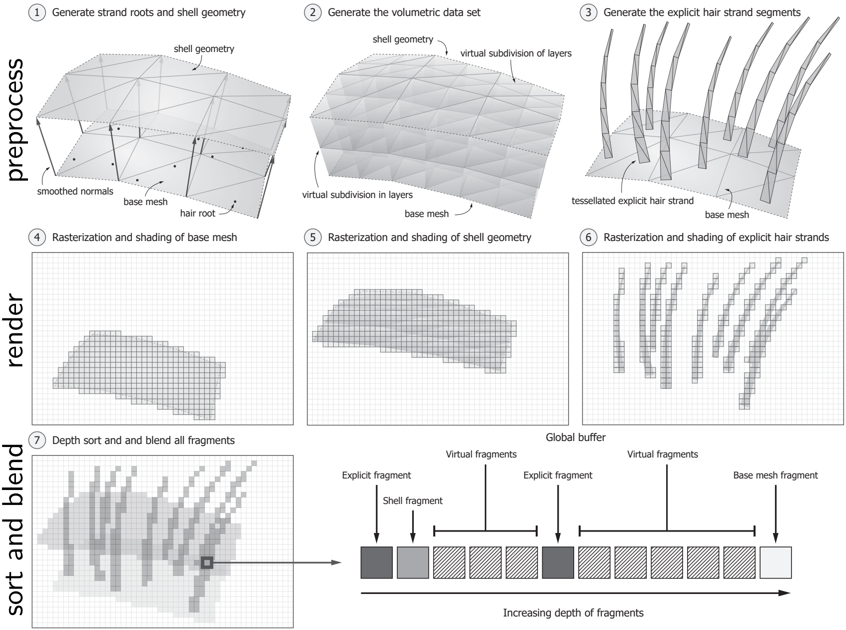
(implicit) Prismatic shell volume for undercoat fur.

- Densities: 2D noise with randomization of uv-coordinates that increases with the distance to the base mesh.

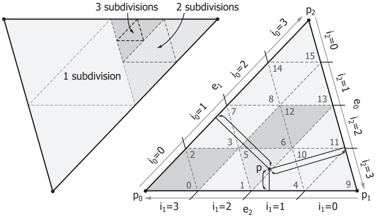
(explicit) Cubic Bézier tubes with variable radius for guard hairs.

- Random placement according to density in textures.
- Bending according to gravity.

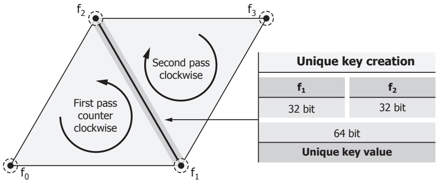
Hybrid fur rendering pipeline



Prismatic shell volume with Loop subdivision

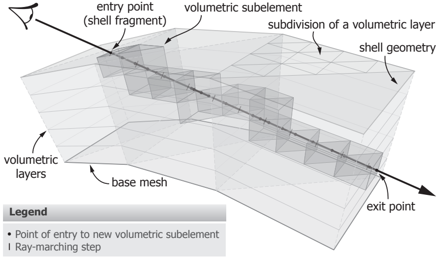


subdivision and indexing



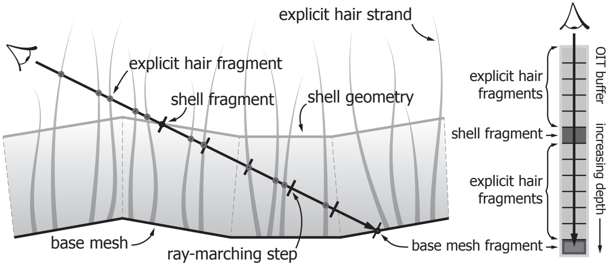
neighbor data structure

- Loop subdivision enables fast transformation from position to subelement index of a prismatic voxel.
- Neighbor data enables ray marching without ray-voxel intersection tests.

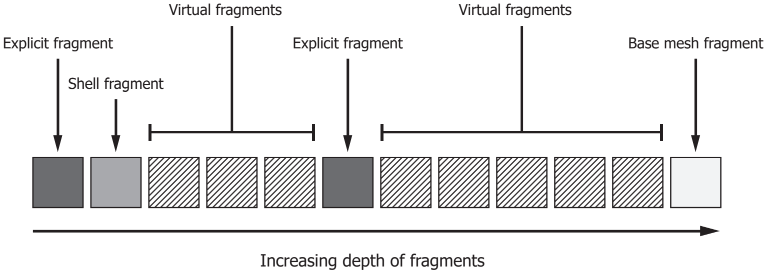


ray marching

Blending with order independent transparency



- Reduce shell fragment alpha based on explicit hair fragments behind it (hack) or insert virtual fragments for scattering events (accurate).

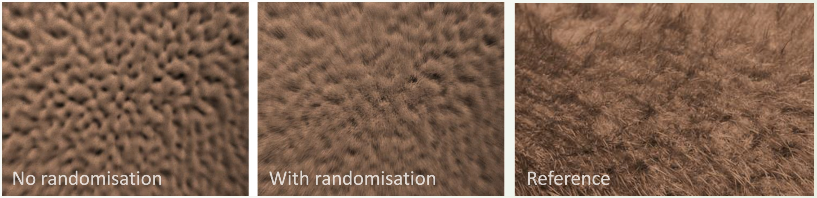


Appearance modeling based on reference photos

guard hairs

undercoat hairs

- Mink furs kindly loaned to us by Kopenhagen Fur.
- Reference photos were very useful in the modeling process.
- Example: importance of uv-randomization in volume densities.



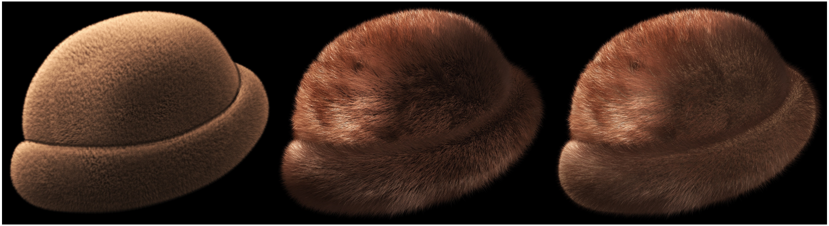
Reference photo of brown mink fur

Guard hairs as explicit hair strands

Hybrid fur

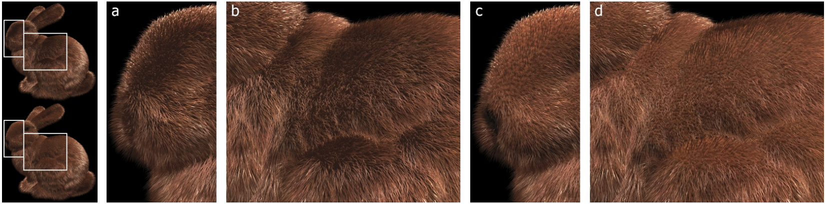
Reference photo of brown mink fur

Visual importance of the implicitly defined undercoat fur



undercoat guard hairs hybrid

- Resolution: $(4\times)$ 3840×2274 downsampled to 1920×1137.
- Hat: 5632 triangles. Total render time: 12.7 s.
- Stanford Bunny: 69451 triangles. Total render time: 9.9 s.



guard hairs hybrid

Performance

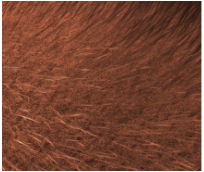
- Preprocessing time: cylinder 2.4 s, hat 1.8 s, bunny 1.3 s.
- Online render time: cylinder 1.4 s, hat 2.7 s, bunny 2.1 s.
- Low resolution (1024×1024 downsampled to 512×512) online render time: cylinder 0.5 s.
- Conventional ray-voxel intersection with d subdivisions: Online render time becomes a factor $3 + 0.4d$ larger.

- Memory consumption around 4.5 GB (alpha-based blending).
- Virtual fragments with average fragments per pixel of 30 increases memory consumption to 7.8 GB.

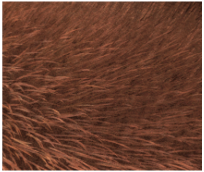
- There is a memory vs. online render time trade-off.
- For the fur cylinder with reference photo:
  - The volumetric undercoat fur costs around 82k explicit hairs.
  - The photographed fur has around 3.8 million undercoat hairs.

Conclusion

- Key contributions:
  - Pipeline for combined rendering of a light scattering shell volume and explicitly defined hair strands (or particles).
  - Efficient ray marching of a prismatic subdivision shell volume, which is easy to use with triangle meshes.
  - First test with undercoat fur as a scattering volume together with guard hairs as explicitly defined geometry.
- As graphics hardware improves, we should use:
  - Virtual fragments for more accurate blending.



alpha-based



virtual fragments

  - Deep opacity maps for more accurate self-shadowing.
  - Dual scattering for approximating multiple scattering.
  - Physically-accurate hair reflectance and phase function.

Thank you for your attention