Exploiting Local Orientation Similarity for Efficient Ray Traversal of Hair and Fur

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Challenges of Hair Geometry

• Path Tracing hair requires high sampling rates to reduce noise and aliasing

  ➔ Our approach helps by improving traversal performance

• Long and thin structures are challenging to bound using AABBs

  ➔ Our approach uses oriented bounding boxes to produce much tighter bounds

• Many million hairs are common (in particular for furry animals)

  ➔ We use direct ray/hair intersection to keep memory consumption low
    (tessellation impractical because of high memory consumption)
Previous Work

• Path Tracing Hair
  • [Moon and Marschner 2006]: Simulating Multiple Scattering in Hair Using a Photon Mapping Approach
  • [Ou et al. 2012]: ISHair: Importance Sampling for Hair Scattering

• Oriented Bounding Box (OBB) Hierarchies
  • [Lext and Akenine-Möller 2001]: Towards Rapid Reconstruction for Animated Ray Tracing
  • OBBs used in commercial renderers

• Ray/Curve Intersection
  • [Sederberg and Nishita 1990]: Curve Intersection using Bezier Clipping
  • [Nakamaru and Ohno 2002]: Ray Tracing for Curve Primitive
Hair Representation

• Hair subdivided into individual hair segments (done in application)

• Hair segments represented as cubic bezier curves (4 control points) with interpolated radius (4 radii)
Bounding Representations

- **Axis Aligned Bounding Box (AABB):**
  lower and upper bounds in x,y,z in world space

- **Oriented Bounding Box (OBB):**
  lower and upper bounds in x,y,z in rotated space
Bounding Diagonal Hair Segment

Axis aligned bounds

- loose
  - many false positives

Oriented bounds

- tight
  - few false positives
Bounding Diagonal Hair Segments

Axis aligned bounds

- significant overlap
- many traversal steps

Oriented bounds

- minimal overlap
- few traversal steps
Local Orientation Similarity

• Neighboring hairs exhibit natural similarity in orientation

• For real hair, collisions cause similar orientation

• Synthetic hair mostly mimics real hair
Bounding Groups of Similarly Oriented Hairs

• Groups of equally oriented hair segments are effectively bounded by OBBs

⇒ OBB hierarchy efficient for similarly oriented hair segments
Our Approach

• Use mixed AABB/OBB hierarchy with fast direct ray/curve intersection

• Exploits local orientation similarity to be efficient.

• No advantage for random hair distributions.
Mixed AABB/OBB Hierarchy

- 4 wide Bounding Volume Hierarchy to make effective use of 4-wide SSE

- Node types
  - **AABB nodes** store 4 AABBs plus 4 child references
  - **OBB nodes** store 4 OBBs plus 4 child references
  - **Leaf nodes** store short lists of individual cubic bezier curves

- Triangles handled in separate BVH simplifies the implementation.
AABBs versus OBBs

- OBBs bound better, but more expensive ➔ tradeoff
  - Towards the root AABBs are best as hair segments are small relative to bounding box
  - Towards the leaves OBBs are best as oriented bounds can tightly enclose hair strands

➔ Few nodes store AABBs and many OBBs

➔ Many AABB nodes and few OBB nodes get traversed

<table>
<thead>
<tr>
<th>Performance</th>
<th>AABB only</th>
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<th>AABB+OBB</th>
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<tbody>
<tr>
<td></td>
<td>100%</td>
<td>146%</td>
<td>186%</td>
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</table>
Uncompressed OBB Nodes

• Stores 4 OBBs in Struct of Array Layout for effective use of SSE

• OBB stored as affine transformation (3x4 matrices) that transforms OBB to unit AABB

• Fast ray/OBB intersection by first transforming ray and then intersecting with unit AABB

• Requires 224 bytes per node

⇒ about 2x the size of an AABB node

```c
struct UncompressedOBBNode
{
    float[4] matrix[3][4];
    Node* children[4];
}
```
Compressed OBB Nodes

- Stores one shared quantized (signed chars) rotation that transforms the OBBs to AABBs
- Stores merged AABBs (after rotation) of all 4 children using floating point
- Stores quantized (unsigned chars) AABBs of each child relative to merged AABB
- Requires only 96 bytes per node (less than half of uncompressed)

```c
struct CompressedOBBNode {
    char matrix[3][4];
    float min_x, min_y, min_z;
    float max_x, max_y, max_y;
    uchar cmin_x[4], cmin_y[4], cmin_z[4];
    uchar cmax_x[4], cmax_y[4], cmax_z[4];
    Node* children[4];
};
```
AABB/OBB Hierarchy Construction

• Traditional top down build using SAH heuristic [Wald 2007]

• Handling lists of bezier curves (not lists of bounding boxes)
  ➔ control points needed for spatial splits
  ➔ control points allow to compute precise bounds in different spaces

• Use lowest SAH split from multiple splitting heuristics

• Some splitting heuristics operate in a special hair space

• Spatial splits [Stich et. al.; Popov et. al.] can make the approach more robust by handling challenging cases
Split Heuristics

- AABB Split Heuristics
  - Object Binning (16 bins) in world space
  - Spatial Splits (16 bins) in world space

- OBB Split Heuristics
  - Object Binning (16 bins) in hair space (most important)
  - Spatial Splits (16 bins) in hair space
  - Similar Orientation Clustering
Hair Space

• Hair space used for binning and calculating OBBs of nodes

• Hair space is a coordinate space with one axis well aligned with a set of hair curves

• Only rotations used to be area preserving

• Calculation
  • calculate candidate spaces (4 in the paper) aligned with main direction (start to end point) of random hairs
  • pick space where sum of surface areas of bounding boxes of hair is smallest
Similar Orientation Clustering

• Can separate two crossing hair strands ➔ No single hair space will work well

• Calculation
  • pick random hair A
  • pick hair B that is maximally misaligned with hair A
  • cluster according to main direction of hairs A and B
  • bound clusters according to space aligned with main direction of A and B

• Gives about 5% higher rendering performance
4-wide AABB/OBB Hierarchy Construction

• Split multiple times to fill up all 4 children (pick largest node or node with highest SAH gain)

• If only „AABB heuristic“ splits create AABB node

• If one split was an „OBB heuristic“ split create OBB node and store OBB aligned with hair space computed for each child

→ SAH decides where to use which node type
AABB/OBB Hierarchy Traversal

• Modified highly optimized BVH4 single ray traversal kernel of Embree
• Kept fast path for AABB node handling
• Added slow path for OBB node handling
• Added fast ray/hair segment intersection
Ray-Hair Segment Intersection

• Use 8-wide AVX to generate 8 points on curve in parallel using precalculated Bezier coefficients $a, b, c, d$:

$$\text{avxf } p = a*p_0 + b*p_1 + c*p_2 + d*p_3$$

• Intersect ray using 8-wide AVX in parallel with 8 line segments using test by [Nakamaru and Ohno 2002]

• 8 segments work well for our models
  → rarely very curved hair segments need pre-subdivision
Benchmark Settings

- Dual Socket Intel® Xeon® E5-2697 (AVX2, 2x 12 cores @ 2.7 GHz, 64GB memory)
- 1M pixel resolution, path traced including shading (50% shading, 50% tracing)
- Representative movie content from Dreamworks

**Tighten**
- 420k triangles
- 2.2M curves

**Tiger**
- 83k triangles
- 6.5M curves

**Sophie**
- 75k triangles
- 13.3M curves

**Yeti**
- 82k triangles
- 153M curves
## Results

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Measured on Dual Socket Intel® Xeon® E5-2697, 12 cores @ 2.7 GHz
# Results: Using Ray/Curve Intersector

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- Using our ray/curve intersector reduces performance by 15% at 1/4\(^{th}\) the memory consumption

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## Results: Triangles Consume too much Memory

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➡️ Out of memory, even with 64GB of memory and tessellation into only 8 triangles.

Measured on Dual Socket Intel® Xeon® E5-2697, 12 cores @ 2.7 GHz
### Results: Adding OBBs

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Adding OBBs gives 80% speedup for 30% higher memory consumption.

Measured on Dual Socket Intel® Xeon® E5-2697, 12 cores @ 2.7 GHz
### Results: Adding Spatial Splits

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**spatial splits give 15% speedup for 60% higher memory consumption**

Measured on Dual Socket Intel® Xeon® E5-2697, 12 cores @ 2.7 GHz
## Results: Adding Compression

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→ spatial splits and compression give 13% speedup for similar memory consumption

Measured on Dual Socket Intel® Xeon® E5-2697, 12 cores @ 2.7 GHz
Video

- Path tracing with up to 10 bounces @ about 1M pixels
- 2x Intel(R) Xeon(R) CPU E5-2687W @ 3.10GHz (16 cores total)
Conclusion and Future Work

- AABB/OBB hierarchy gives almost 2x speedup for hair geometry
- Need to improve build performance currently 20x slower than building standard BVH over curve segments
- Handling triangles in same BVH could give additional benefit.
- Support for Motion Blur is important for movie rendering.
Questions?

Source code for Xeon and Xeon Phi available as part of Embree 2.3.1, https://embree.github.com