STBVH: A Spatial-Temporal BVH for Efficient Multi-Segment Motion Blur

Sven Woop, Attila Áfra, Carsten Benthin

Intel Corporation
Motion Blur

- Fast moving geometry gets blurred for long shutter times
- Often fast moving geometry moves on a straight line (linear motion blur)
- Sometimes fast curved motion (e.g. rotating wheel, fight scenes, spinning dancer, flying bird, etc.)

⇒ Multi Segment Motion Blur required
Multi Segment Motion Blur

- Represent curved motion as sequence of time steps to be linearly interpolated
- Typically equidistant time steps and often different number of time steps per geometry

![Diagram showing 4 primitive segments over 5 time steps](image-url)
Previous Work

Linear Motion BVH using OBB Hyper-trapezoids [Hou et al. 2010]
- Works well for linear motion but inefficient for curved motion.

Multiple Linear Motion BVHs for sufficiently large number of time segments [Embree v2.12.0]
- High performance but memory consumption can be arbitrarily bad.

Sequence of AABBs per BVH node [Grünschloß et al. 2011]
- One BVH topology for entire motion, calculate segment to interpolate per traversal step, packet techniques have to gather bounds

4D kd-tree [Olsson 2007]
- Can shrink time range to simplify motion, kd-tree not good at bounding linear motion, no good build algorithm described

4D BVH using 12 fixed slab directions [Glassner 1988]
- Expensive to traverse (24 distance tests to mostly non-axis aligned planes), fixed directions do not align optimally with motion direction

Combining separate renderings for sufficiently many time segments
- No adaptive noise reduction possible, interactive preview not possible
4D Spatial-Temporal BVH (STBVH)

- N-ary BVH (4 or 8 wide) [Ernst 2008, Dammertz 2008]
  - SOA layout allows efficient use of SIMD instructions during traversal

- Stores spatial *linear bounds* [Qiming Hou et al. 2010]
  - Pair of AABBs that bound the geometry for each time when linearly interpolated to the respective time
  - Efficient support for the common case of linear motion

- Stores temporal bounds as time range [Olsson 2007, Glassner 1988]
  - Efficient support of curved motion through time range reduction

- Two node types for improved performance
  - Spatial-temporal nodes (stores linear bounds and time range)
  - Spatial nodes (stores linear bounds only)
STBVH Advantages

- Efficient handling of different number of time steps per geometry
  - E.g. high temporal resolution possible for main character
  - Large memory savings compared to Embree 2.12.0 implementation

- Efficient handling of longer animations
  - Renderers with large setup times can render multiple frames with one STBVH

- Reduced memory consumption in case of unnecessarily high number of time steps
  - For these parts time ranges do not have to get reduced
Temporal Spatial Bounds Example 1
Temporal Spatial Bounds Example 2

Global linear bounds allow direct interpolation with ray time.
Minimal Traversal Changes

- Ray/box intersection with box interpolated to ray time
- Additional check for time bounds in case of spatial-temporal node
Motion Blur Surface Area Heuristic (MBSAH)

- Motion Blur Surface Area Heuristic
  - \( C_{\text{leaf}}(X) = |X|_s \cdot C_I \)
  - \( C_{\text{split}}(X, X_0, X_1) = C_T + P(X_0|X) \cdot C_{\text{leaf}}(X_0) + P(X_1|X) \cdot C_{\text{leaf}}(X_1) \)

- Where
  - \( X \) is the set of pairs of primitives and time ranges
  - \(|X|_s\) is the sum of the number of primitive segments active in the time range
  - \( P(Y|X) = \frac{SA'(Y)}{SA'(X)} \cdot \frac{T(Y)}{T(X)} \)
  - \( T(X) \) calculates the size of the merged time bounds over \( X \)
  - \( SA'(X) \) calculates the surface area of the center time bounds of the linear bounds of \( X \)
MBSAH Advantages

- Handling primitives plus time range
  - Makes time splits of primitives possible

- Counting primitive segments active in time range
  - Increases cost for geometries with many time steps
  - Splitting time at discrete time boundaries produces optimal SAH

- Surface area of linear bounds
  - More accurate than previous approaches
  - Up to 10% render performance improvement for some scenes
STBVH Build

- Top-down construction using MBSAH
- Build primitive represents primitive for current time range
  - Stores linear bounds and number of active primitive segments
- Object split
  - Bin build primitives in 3 dimensions using centroid of center time bounds
  - Splits build primitives into two disjoint sets with current time range unchanged
- Temporal split
  - Splits current time range at center time (adjusted to hit discrete time boundary)
  - Generate build primitives for both time ranges (most primitives valid in both time ranges)
MBSAH: Temporal Split

Object split

Temporal split

Best
MBSAH: Spatial Split

Object split

Temporal split

Best
Results

Llama
3 time steps: 7M primitives
9 time steps: 1.7M primitives

Barbershop
3 time steps: 1.4M primitives
5 time steps: 2.8M primitives
9 time steps: 3.9M primitives

Train
3 time steps: 0.3M primitives
17 time steps: 2.0M primitives

Turtle Barbarian Crowd
2 time steps: 7.5M primitives
6 time steps: 2.8M primitives
15 time steps: 0.1M primitives

Turtle Barbarian
15 time steps: 0.1M primitives

Turtle Barbarian Rotate 0.5x
9 time steps: 0.1M primitives
Results

- Comparing against LBVH of Embree 2.12.0
  - Separate Linear Motion BVHs for maximal number of linear time segments
  - We integrated our STBVH into Embree thus share algorithmic details of traversal and build
- Only motion blur geometry for benchmarks
- Intel® Xeon® E5-2699 v4 workstation (Broadwell 22 cores, 2.2 GHz)
Memory Consumption

Smaller BVH due to varying number of time segments

<table>
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<tr>
<th>Scene</th>
<th>LBVH</th>
<th>STBVH</th>
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Similar BVH size
Build Performance

Faster due to smaller BVH

Slower due to linear bounds binning

Llama
Barbershop
Train
Turtle Barbarian Crowd
Turtle Barbarian
Turtle Barbarian Rotate 0.5x

LBVH
STBVH
## Render Performance

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- **Llama**
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**Faster due to less memory traffic**

- Competitive but slightly slower
Questions?

“High Performance Rendering Appliance” demo at Intel booth #807 at SIGGRAPH