Acceleration Data Structures for Ray Tracing on Mobile Devices

Nuno Sousa[1], David Sena[2], Nikolaos Papadopoulos[2] and João Pereira[1]
[1]*Instituto Superior Técnico/Inesc-ID, Universidade de Lisboa, Lisboa, Portugal*
[2]*Samsung R&D UK, Staines, U.K.*

Keywords: Ray Tracing, Acceleration Structures, Mobile Environment, Android, OpenGL ES.

Abstract: Mobile devices are continuously becoming more efficient at performing computationally expensive tasks, such as ray tracing. A lot of research effort has been put into using acceleration data structures to minimize the computational cost of ray tracing and optimize the use of GPU resources. However, with the vast majority of research focusing on desktop GPUs, there is a lack of data regarding how such optimizations scale on mobile architectures where there are a different set of challenges and limitations. Our work bridges the gap by providing a performance analysis of not only ray tracing as a whole, but also of different data structures and techniques. We implemented and profiled the performance of multiple acceleration data structures across different instrumentation tools using a set of representative test scenes. Our investigation concludes that a hybrid rendering approach is more suitable for current mobile environments, with greater performance benefits observed when using data structures that focus on reducing memory bandwidth and ALU usage.

1 INTRODUCTION

The hardware of mobile devices has improved significantly over the past few years. There are, however, limitations, and developers are always searching for optimizations that allow them to make the best use of available hardware. Nevertheless, today a mobile device is capable of rendering graphically intensive applications with reasonable quality and performance.

Ray tracing is a rendering technique capable of producing highly realistic results at higher computational cost than rasterization based approaches. With the release of technologies like DirectX Raytracing (DXR), native support for hardware accelerated ray tracing is starting to become more accessible to an end user.

The high computational cost of ray tracing can be reduced with the use of acceleration data structures, a topic that has been primarily researched for desktop computers. Our main objective is to present a comparative study of the performance of these data structures on mobile platforms and document their characteristics.

2 PREVIOUS WORK

The idea of using ray shooting for the generation of images was first introduced by (Appel, 1968). Several other techniques have since been developed that provide much higher visual fidelity by simulating visual effects like reflections (Whitted, 1979), soft shadows (Cook et al., 1984), depth-of-field (Cook et al., 1984) and even global illumination (Kajiya, 1986). This, however, is outside the scope of our work. The focus of this research is the performance of acceleration data structures and not the visual fidelity achieved with different ray tracing techniques.

2.1 Acceleration Data Structures

Acceleration data structures can be used to reduce the number of ray-primitive intersection tests. An acceleration data structure algorithm transforms scene data to a format that minimizes the number of intersection tests at runtime and optimizes the use of hardware.

For our research we focused on the traversal performance of KD-Trees and Bounding Volume Hierarchy (BVH). Both structures make use of Surface Area Heuristic (SAH) (Goldsmith and Salmon, 1987) to determine the best splitting point for each node that is being subdivided.

Sousa, N., Sena, D., Papadopoulos, N. and Pereira, J.
Acceleration Data Structures for Ray Tracing on Mobile Devices.
DOI: 10.5220/0007575403320339
In *Proceedings of the 14th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications (VISIGRAPP 2019)*, pages 332-339
ISBN: 978-989-758-354-4

2.1.1 Bounding Volume Hierarchies

Bounding Volume Hierarchies are based on bounding volumes (Kay and Kajiya, 1986). A BVH is a tree in which the root consists of a bounding volume that encloses the whole scene. Each internal node is a bounding volume of a subset of objects of its parent node. The leaves contain actual geometry to test against.

The BVH can be subdivided, for example, by using the median of the centroids of the enclosed objects or by using SAH.

In this work we chose to focus on the following traversal algorithms:

- Stack-less Parent-Link Traversal - a link-based algorithm that tries to provide the same traversal order of the stack based algorithm while being stack-less (Hapala et al., 2011).
- Restart Trail Traversal - This algorithm tries to adapt the KD-restart algorithm used to traverse KD-trees, to be used with Bounding Volume Hierarchies (BVHs) (Laine, 2010).

2.1.2 KD-Trees

First introduced as a method for searching of points in a k-dimensional space (Bentley, 1975), KD-trees are a specific case of binary space partitioning Binary Space Partitioning (BSP).

Just like BVHs spatial subdivision can be based on SAH. An optimised $O(NlogN)$ construction algorithm introduced by (Wald and Havran, 2006) which used an ordered event list with special list splitting rules.

Our work focused on Graphics Processing Unit (GPU) based algorithms (Hapala and Havran, 2011), more specifically:

- Kd-Push-Down Traversal - this algorithm expands Kd-Restart (Horn et al., 2007), which works by moving a point along the ray and finding the leaf where the point is located. By keeping the lowest depth-wise node that contains the interval of intersection in its entirety, this node can then be used instead of the root node when restarting the search.
- Kd-Backtrack Traversal - this algorithm adds to each node the corresponding bounding box and a pointer to the parent node (Foley and Sugerman, 2005) to avoid restarting the search from the root node.

2.2 Mobile Environment

The system on chip architectures of mobile devices have restrictions on the amount of power they can draw and, due to the small form factor, the amount of heat they are able to dissipate. As a result, computational resources are more limited than on desktop computers.

3 IMPLEMENTATION

This research focuses on mobile environments, running Android, and was conducted in partnership with Samsung UK. The following sections will describe how the application was implemented, which ray tracing algorithms were used as well as which data structures were implemented. We also describe the different rendering approaches used.

3.1 Ray Tracing Implementation

We implemented Whitted ray tracing (Whitted, 1979) with a ray spawned for each pixel of the framebuffer and a subsequent ray spawned for each light visibility query when an intersection is found. We implemented the ray-triangle intersection algorithm by (Möller and Trumbore, 2005) and for Axis Aligned Bounding Box (AABB) ray intersections we used the ray-box intersection algorithm by (Williams et al., 2005).

We implemented different data packing arrangements of primitives using Shader Storage Buffer Object (SSBO). Our initial approach was to store each triangle vertex and each normal as a $vec3$ with padding. In our second approach we used the padding of the three vertices to store the first normal and minimize the size per primitive. Our last approach was based on the fact that, while doing intersection testing, normals are not used. We split the vertices and normals into separate SSBOs to reduce redundant memory accesses.

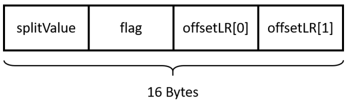
3.2 Implementation of Acceleration Data Structures

For the GPU rendering methods we chose to implement only KD-Trees and BVHs instead of Regular Grids because they are consistently outperformed by BVHs and KD-Trees apart from very specific situations (Thrane and Simonsen, 2005).

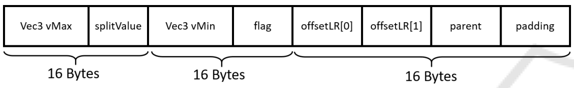
3.2.1 KD-Tree Implementation

The construction of KD-Trees in our implementation is done using the SAH algorithm (Wald and Havran, 2006). Our implementation allows for the creation of empty leaf nodes but does not perform triangle clipping. By experimenting with different values for $C_{traversal}$ and $C_{intersection}$, we concluded that mobile architectures tend to favour wider and shallower trees. We found a value of 3.0 for $C_{traversal}$ and 1.5 for $C_{intersection}$ to yield good results.

The memory layout for KD-Tree nodes varies according to which traversal algorithm is being used.



(a) KD-Pushdown node layout



(b) KD-Backtrack node layout

Figure 1: Layouts of KD-Tree nodes. vMin and vMax represent the node bounding box.

Another difference between trees for the two traversal methods is that while building the tree for the KD-Backtrack traversal method, we do not allow for perfectly flat nodes, i.e. nodes that have zero length on one of the axis. This is done to avoid precision related issues while traversing the tree. We implemented the KD-Pushdown and KD-Backtrack algorithms using the node layouts shown in Figure 1.

3.2.2 BVH Implementation

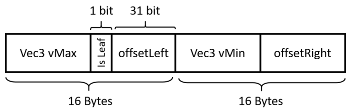
In our implementation, the construction of BVHs is done using an altered version of the construction algorithm (Wald and Havran, 2006) that was also used in the KD-Trees construction. Like with KD-Trees, after experimenting with several values, we came to the conclusion that, again, wider, shallower trees tend to perform best. As such, the values chosen for $C_{traversal}$ and $C_{intersection}$ were, again, 3.0 and 1.5 respectively.

The memory layout for BVH nodes also varies according to which traversal method is being used. The possible layouts are shown in Figure 2.

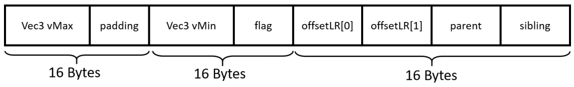
For GPU traversal we implemented Trail traversal along with the Parent-Link traversal algorithm.

3.3 GPU Rendering Methods

Our implementation used multiple rendering approaches. Regardless of the rendering method chosen, our implementation starts by constructing the selected acceleration structure along with the auxiliary structures for primitive storage. These structures are then copied to GPU memory as Shader Storage Buffer Objects (SSBOs). The application also creates and uploads a Vertex Array Object (VAO) containing a full-screen quad that is then used for every rendering method. The drawing process, however, changes according to which rendering approach is selected:



(a) BVH Trail traversal node layout



(b) BVH Parent traversal node layout

Figure 2: Layout of BVH nodes. vMin and vMax represent the node bounding box.

- Fragment Shaders - the application renders a full-screen quad using a very simple vertex shader. The fragment shader is then responsible for ray tracing the corresponding pixel. In this case, all the code for ray tracing and structure traversal is contained in the fragment shader.
- Compute Shaders - the application performs a two step process. In the first step, the application dispatches the necessary compute workgroups so that each thread processes a pixel of the final image. The result of this first step is stored in an Image Buffer which is then utilized in the second step as an input texture. The second pass simply draws a full-screen quad, using the texture generated in the first step.
- Hybrid Shading - the application, not only creates a VAO containing the full-screen quad, but also a second VAO containing the entire geometry for the scene being rendered. This second VAO is used in the first phase of the rendering process, where the application issues a drawcall that rasterizes all primitives. This first phase stores the calculated normals into a color attachment. From this first step a depth buffer is also generated. These two buffers are then used on the second phase of the drawing process where the full-screen quad is rendered. The values in the buffers are used to create and cast the shadow ray which then triggers a structure traversal. For this rendering method, all the ray tracing logic is in the fragment shader of the second pass.

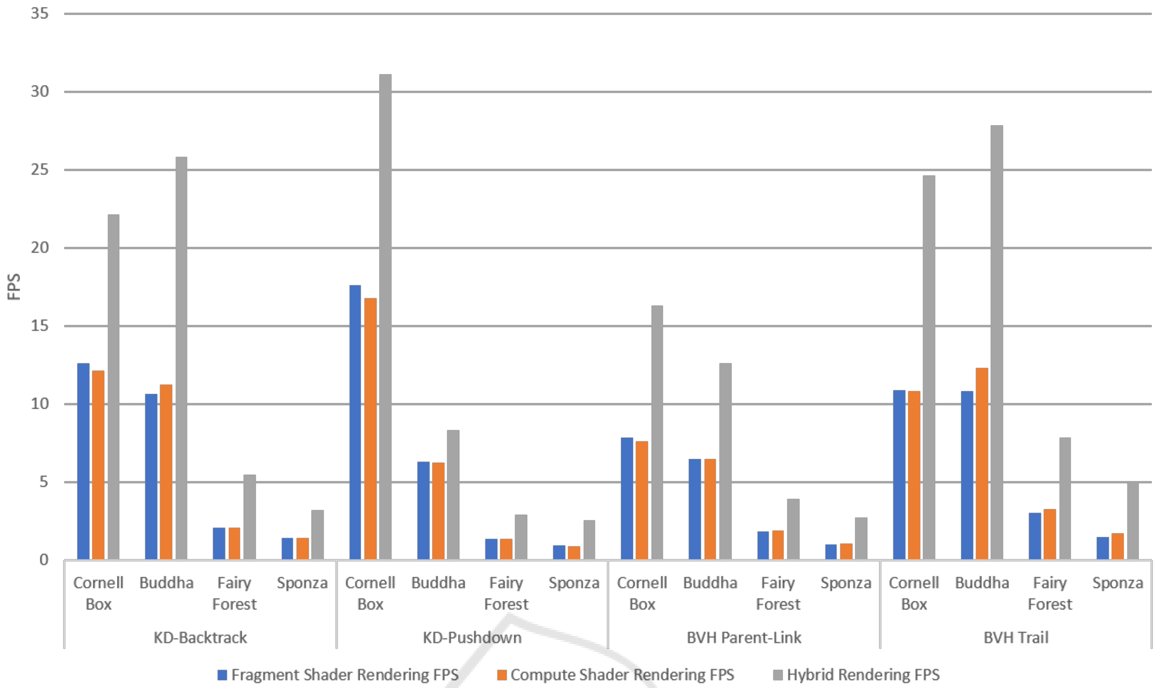


Figure 3: Graph comparing the performance of different rendering methods.

4 EVALUATION

To evaluate the performance of the different algorithms, we profiled our implementation by collecting metrics in app and using external instrumentation tools.

The application was developed using OpenGL ES and tested on a Samsung Galaxy S8 (Model SM-G950U) with a 64 bit Qualcomm Snapdragon 835 system-on-chip with a Qualcomm Adreno 540 GPU provided by Samsung Research, UK.

4.1 Application Metrics

At the rendering stage, several measurements are collected in order to evaluate overall performance:

- Framerate - How many times the image is updated per second. Frametime expressed in milliseconds, while more accurate, is harder to measure on mobile due to hardware and architectural restrictions.
- Rays per Second - expressed in millions of rays per second. Rays-per-Second (RPS) more accurately describes the raw ray tracing power of the underlying hardware.
- Structure Size - expressed in KBytes. Represents the overall size of the generated acceleration structure.

The application allows to visualize a heatmap representing the number of node traversals for each pixel. As an effort to keep results consistent, we consider that a node is traversed when it is fetched from the acceleration structure SSBO.

4.2 External Tools

The Qualcomm Snapdragon Profiler allows developers to profile devices with Snapdragon processors. The application provides several metrics of interest to our work:

- SP Memory Read - Number of bytes read from memory by the Shader Processors per second.
- % Shader ALU Capacity Utilized - % of maximum shader ALU capacity that is being utilized.
- % Time ALUs Working - % of time the ALUs are working while the shaders are busy.
- ALU/Fragment - Average number of ALU instructions performed per fragment.

4.3 Test Scenes and Test Methodology

For our tests we used a number of different scenes such as the Cornell Box, the Cornell Buddha, the Fairy Forest and the Crytek Sponza.

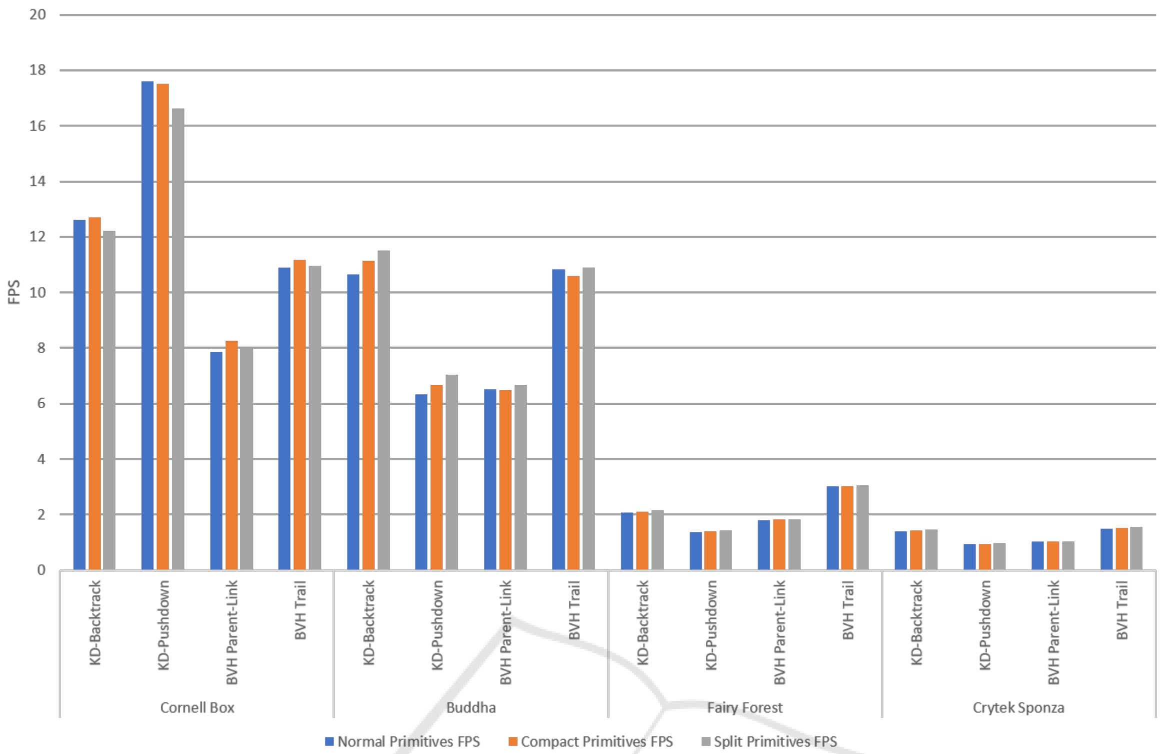


Figure 4: Graph showing performance for different primitive layouts.

The application always renders the resulting image at 1024x1024 resolution. We also restart the application between every test.

5 RENDERING TECHNIQUES COMPARISON

We implemented three different rendering approaches, and for each approach we profiled the performance of different traversal methods across different scenes. While Fragment and Compute rendering had similar performance, as shown in Figure 3, the hybrid rendering approach distinguished itself by having better performance. This is due to the higher computational cost of ray tracing when compared with rasterization.

Overall, our results show that using hybrid rendering is the best approach when implementing ray tracing on mobile. However, different ray tracing algorithms may benefit from using Fragment and Compute Shader based rendering.

6 PRIMITIVE LAYOUT COMPARISON

As shown in Figure 4, we ran a series of tests to analyse the performance of the different primitive layouts. Results show that a compact layout does not always equate to better performance as it needs a few extra instructions to retrieve the stored normal. The split layout on the other hand, consistently yields either similar or better results.

To better understand the impact of these changes when accessing memory, we performed a bandwidth analysis using the Cornell Box and Buddha scenes. The results are shown in Figures 5 and 6.

The results show that there is a reduction in memory bandwidth from using the compact and split layouts, with split layout producing the best results. Having vertices and normals separated means that no bandwidth is wasted on normals that are not being used. This maximizes the number of vertices fetched each time which means the number of overall fetches is reduced.

Scenes with higher complexity require more accesses to the data structures containing the geometry and thus, optimization of primitive layout becomes more important because of the impact in memory bandwidth utilization.

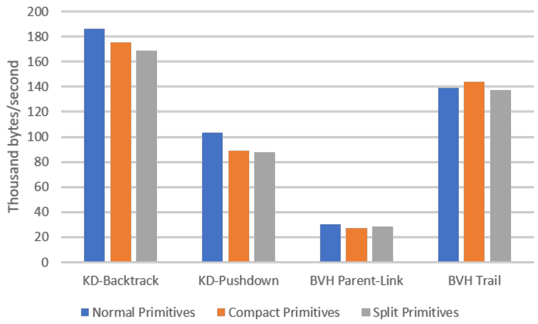


Figure 5: Memory bandwidth usage when varying primitive layout for the Cornell Box Scene.

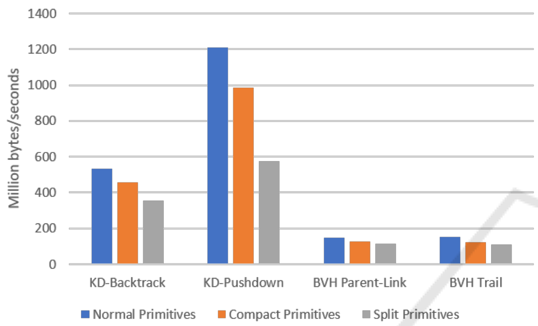


Figure 6: Memory bandwidth usage when varying primitive layout for the Buddha Scene.

7 ACCELERATION DATA STRUCTURE COMPARISON

Acceleration data structures are essential for the efficiency of ray tracing algorithms and as such have an impact on performance. In the following sections we will present and discuss the results we obtained with regards to computation cost and memory utilization.

7.1 Performance

To evaluate the performance of the different data structures, we conducted a series of tests for the traversal methods we chose across different scenes. For these particular tests we only used the Fragment Shader renderer along with a normal primitive layout.

Figure 7 shows the results obtained from all the test runs. Whilst the performance of the KD-Pushdown traversal excels in scenes with a lower number of primitives, it quickly deteriorates in scenes with higher geometric complexity. In contrast, BVH Trail traversal performs better in more complex scenes.

To understand the performance difference between traversal methods, we created heatmaps for each traversal method and each scene. Figure 8 shows a subset of the generated heatmaps.

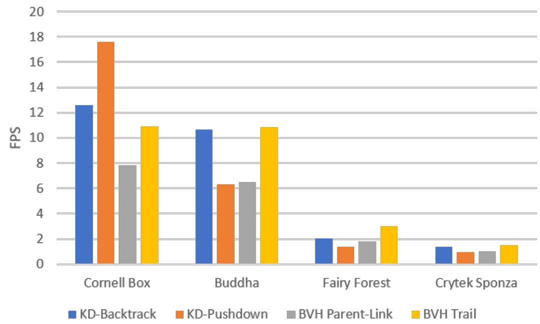
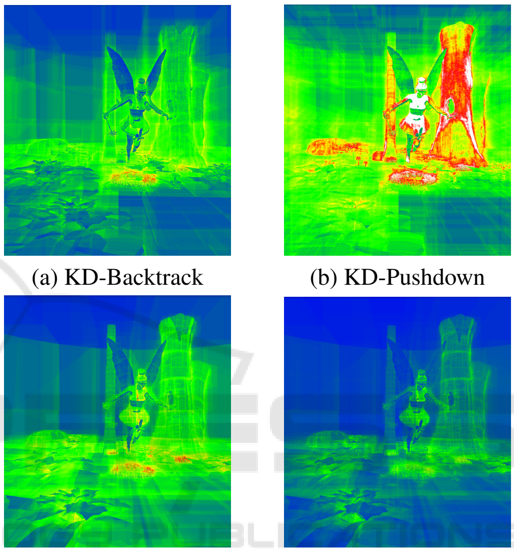


Figure 7: Performance values for acceleration structures.



(a) KD-Backtrack (b) KD-Pushdown

(c) BVH-Parent (d) BVH-Trail

Figure 8: Heatmap of the fairy scene for all structures.

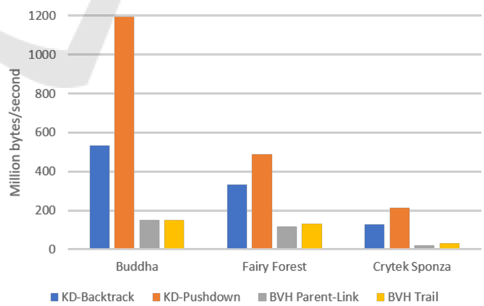


Figure 9: SP Memory Read values for each structure. Values for the Cornell Box were not visible at this scale.

We obtained the best results using BVH Trail. KD-Backtrack and BVH-Parent-Link followed up, yielding similar results to each other. This verifies our previous observations and shows that the number of traversed nodes correlates to the performance of

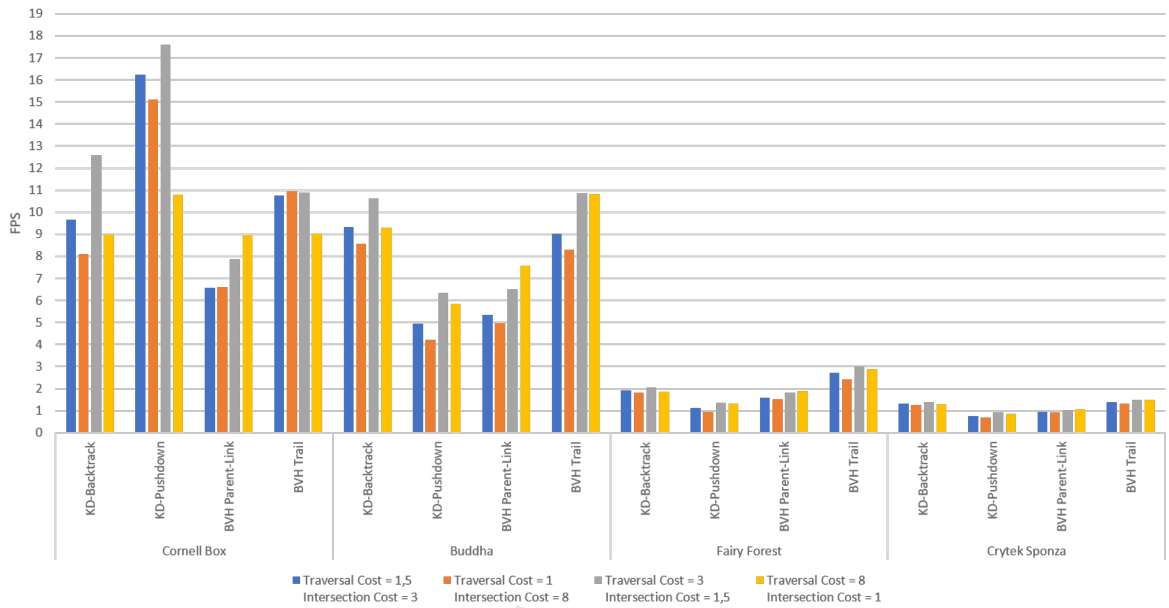


Figure 10: Performance comparison for different SAH cost values.

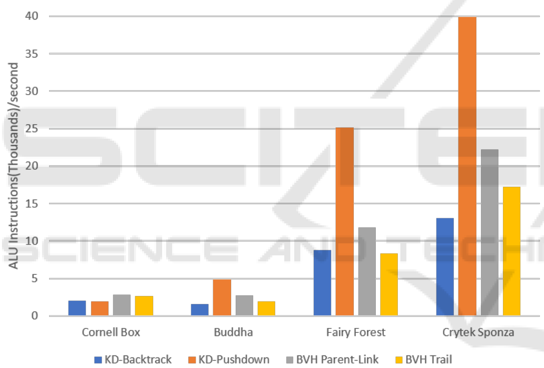


Figure 11: ALU instructions per fragment.

the algorithm. Due to the high cost of bandwidth, we measure its impact. The results are shown in Figure 9.

Algorithms based on KD-Trees consume higher memory bandwidth than those based on BVHs. One explanation is that the increased number of nodes generated by KD-Trees boosts the probability of executing a memory fetch for each new traversed node. This is because each local memory fetch request is less probable to contain the next node that needs to be traversed. In Figure 11 we also analyse the ALU instructions per fragment.

Results show that, the KD-Backtrack algorithm requires the least overall amount of ALU instructions. This is due to the fact that it performs no near-far classification, and, consequently, uses fewer instructions per node traversed than other traversal methods.

On the opposite end, the traversal method with most ALU instructions per fragment is the KD-Pushdown due to the increased number of nodes and extra traversal steps it takes. This, combined with higher memory bandwidth utilization, results in the worst performance across all the traversal methods.

Results show that traversal methods with fewer ALU instructions per fragment have better performance. There is however the exception of the KD-Backtrack traversal, that despite using less ALU instructions has its traversal slowed down due to the high memory bandwidth requirements.

According to these results the performance of the traversal algorithms is limited by a combination of ALU, memory accesses and bandwidth. However, the strongest limitation appears to be the number of traversed nodes, i.e. the number of accesses to the SSBOs that contain the acceleration structure.

7.2 SAH Costs Comparison

One of the ways to optimize KD-Trees and BVHs built using the SAH is to tweak the values for traversal and intersection cost given to the construction function. Usually, having the intersection cost higher than the traversal yields better results. To test this we used four different cost values and a combination of all the scenes and traversal methods.

As shown in Figure 10, having an intersection cost lower than the traversal cost provides the best performance. The results also show that it is best to keep the traversal cost only slightly higher than the intersection cost. Reducing the cost of traversal equates to a higher number of node traversals necessary per pixel. The performance numbers shown in Figure 10 corroborate the previous results showing that the number of traversals correlate to the performance of the traversal algorithm.

8 CONCLUSIONS

Our work focused on providing a performance analysis of different acceleration data structures for ray tracing on mobile devices. Our main goal was to establish a basis for future research into the potential of mobile environments. As for future work, we want to explore the performance of construction methods for dynamics scenes to provide further insight on current mobile hardware capabilities.

ACKNOWLEDGEMENTS

This work was supported by national funds through Fundação para a Ciência e Técnologia (FCT) with reference UID/CEC/50021/2019.

REFERENCES

Appel, A. (1968). Some techniques for shading machine renderings of solids. In *Proceedings of the AFIPS Conference*, pages 37–45.

Bentley, J. (1975). Multidimensional binary search trees used for associative searching. *Commun. ACM*, 18(9):509–517.

Cook, R., Porter, T., and Carpenter, L. (1984). Distributed ray tracing. In *Proceedings of the 11th Annual Conference on Computer Graphics and Interactive Techniques*, pages 137–145.

Foley, T. and Sugerman, J. (2005). Kd-tree acceleration structures for a gpu raytracer. In *Proceedings of the ACM SIGGRAPH/EUROGRAPHICS conference on Graphics hardware*, pages 15–22.

Goldsmith, J. and Salmon, J. (1987). Automatic creation of object hierarchies for ray tracing. *IEEE Comput. Graph. Appl.*, 7(5):14–20.

Hapala, M., Davidovič, T., Wald, I., Havran, V., and Slusallek, P. (2011). Efficient Stack-less BVH Traversal for Ray Tracing. In *Proceedings of the 27th Spring Conference on Computer Graphics*, pages 7–12.

Hapala, M. and Havran, V. (2011). Review: Kd-tree Traversal Algorithms for Ray Tracing. *Computer Graphics Forum*, 30(1):199–213.

Horn, D. R., Sugerman, J., Houston, M., and Hanrahan, P. (2007). Interactive kd tree gpu raytracing. In *Proceedings of the 2007 symposium on Interactive 3D graphics and games*, pages 167–174.

Kajiya, J. (1986). The rendering equation. In *Proceedings of the 13th Annual Conference on Computer Graphics and Interactive Techniques*, pages 143–150.

Kay, T. L. and Kajiya, J. T. (1986). Ray tracing complex scenes. In *ACM SIGGRAPH computer graphics*, volume 20, pages 269–278.

Laine, S. (2010). Restart Trail For Stackless BVH Traversal. In *Proceedings of the Conference on High Performance Graphics*, pages 107–111.

Möller, T. and Trumbore, B. (2005). Fast, minimum storage ray/triangle intersection. In *ACM SIGGRAPH 2005 Courses*.

Thrane, N. and Simonsen, L. O. (2005). A comparison of acceleration structures for gpu assisted ray tracing. Master's thesis.

Wald, I. and Havran, V. (2006). On building fast kd-Trees for Ray Tracing, and on doing that in O(N log N). In *Proceedings of the IEEE Symposium on Interactive Ray Tracing*, pages 61–69.

Whitted, T. (1979). An improved illumination model for shared display. In *Proceedings of the 6th Annual Conference on Computer Graphics and Interactive Techniques*.

Williams, A., Barrus, S., Morley, R. K., and Shirley, P. (2005). An efficient and robust ray-box intersection algorithm. In *ACM SIGGRAPH 2005 Courses*.