A picture containing tool

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Graduation Work Title

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Howest.be

A close up of a card

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Contents

[Contents 1](#_Toc186467172)

[1 Abstract & Key words 3](#_Toc186467173)

[2 Preface 4](#_Toc186467174)

[3 List of Figures 5](#_Toc186467175)

[4 Introduction 6](#_Toc186467176)

[Literature Study / Theoretical Framework 7](#_Toc186467177)

[4.1 Ray Tracing 7](#_Toc186467178)

[1.1.1. Fundamentals 7](#_Toc186467179)

[4.1.2 Acceleration structures 8](#_Toc186467180)

[4.2 sphere tracing (ray marching) 9](#_Toc186467181)

[4.2.1 Fundamentals 9](#_Toc186467182)

[5 Research 12](#_Toc186467183)

[1. Topic 1 12](#_Toc186467184)

[1.1. Subtopic 1 12](#_Toc186467185)

[1.1.1. Subtopic 12](#_Toc186467186)

[2. Topic 2 12](#_Toc186467187)

[1.2. Subtopic 1 13](#_Toc186467188)

[1.2.1. Subtopic 13](#_Toc186467189)

[6 case study 14](#_Toc186467190)

[1. introduction 14](#_Toc186467191)

[2. Modelling 14](#_Toc186467192)

[2.1. Blockout 15](#_Toc186467193)

[2.2. Zbrush 15](#_Toc186467194)

[3. Texturing 16](#_Toc186467195)

[4. Shading 16](#_Toc186467196)

[5. Lighting 16](#_Toc186467197)

[7 Discussion 18](#_Toc186467198)

[8 Conclusion 19](#_Toc186467199)

[9 Future work 20](#_Toc186467200)

[10 Critical Reflection 21](#_Toc186467201)

[11 References 22](#_Toc186467202)

[12 Acknowledgements 23](#_Toc186467203)

[13 Appendices 24](#_Toc186467204)

# Abstract & Key words

**An abstract explains the outline of the paper concisely (the methods, results, etc.). Maximum length of 250 words, preferably both in English and Dutch.**

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# Preface

***A preface is a statement of the author's reasons for undertaking the work and may include personal comments that are not directly relevant to other sections of the thesis or dissertation.* No word count limit.**

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# List of Figures

[Figure 1: Example of a triangle mesh 7](#_Toc186546142)

[Figure 2: The process of ray casting and shading pixels 7](#_Toc186546143)

[Figure 3: AABB for a single triangle 8](#_Toc186546144)

[Figure 4: Complex mesh with BVH applied 9](#_Toc186546145)

[Figure 5: Tree structure for BVH 9](#_Toc186546146)

[Figure 6: Example of SDF output 10](#_Toc186546147)

[Figure 7: Ray marching basic and a missed surface 11](#_Toc186546148)

[Figure 8: Example of both scenarios when raymarching (Hart, 1996) 11](#_Toc186546149)

# Introduction

**In the introduction, you write the background of your topic and discuss the observation that spurred you on to do this research project. Explain the purpose of the paper and present your research question(s) and the hypothesis at the end of this section. This section is typically a couple of pages long.**

# Literature Study / Theoretical Framework

## Ray Tracing

### Fundamentals

#### Triangle meshes

In computer graphics, we need to visualize 3D objects. One of the approaches is a triangle mesh. These consist of a bunch of triangles (Figure 1), each triangle consist of 3 vertices and 3 edges connecting these vertices. (“Triangle Mesh,” 2024)



Figure : Example of a triangle mesh

#### Ray tracing algorithm

The ray tracing algorithm uses these meshes to fill the pixels on the screen with meaningful color. For every pixel on the screen the algorithm casts a ray from the origin through each pixel in an image plane into the scene (the origin is often referred to as the camera or eye point). If the ray intersects with one or multiple meshes, it calculates the shading at that point using the material properties of the closest mesh. The result is used to fill in the pixel the ray was cast for. (Figure 2) This process can be repeated with different origins and directions to incorporate light, reflections and shadows. (*Ray Tracing | NVIDIA Developer*, n.d.)



Figure : The process of ray casting and shading pixels

### Acceleration structures

#### WHY?

If you have very complex geometries and many objects in your scene, then the algorithm executes a lot of unnecessary calculations.

Scenario 1: You have a lot of objects in your scene. The algorithm needs to calculate the intersection for every object just to conclude the ray didn’t hit anything.

Scenario 2: You have a super detailed object with 100 000 primitives. If the algorithm must go over every triangle in that object to find the one it is intersecting with. Then again you have a lot of unnecessary calculations.

To avoid this there are the following acceleration structures.

#### aabb

AABB or Axis Aligned Bounding Box is a common acceleration structure used when ray tracing primitives.

It is a simple box which represents the closed region that contains a triangle mesh. The edges of the box are always aligned with the world axes, meaning that they are parallel to the x, y, and z axes in three-dimensional space. To define the AABB for a triangle mesh you must find the minimum and maximum points along each axis that defines the mesh. Then you can construct the AABB, using the minimum and maximum as two opposite corners of the box. (“Bounding Volume,” 2024; *CSSE451 Advanced Computer Graphics*, n.d.; *What Is AABB in Computing?*, 2024)

The ray tracing algorithm can then calculate ray intersections using the AABB of a mesh, if and only if that is the case, does it calculate further intersections with any of the triangles from the mesh. This method of early out speeds up ray intersection calculations in the case the ray misses an object.

A computer screen shot of a colorful pyramid

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Figure : AABB for a single triangle

#### bvh

BVH or Bounding Volume Hierarchy is another common approach to speed up the ray intersection process.

When you have complex mesh such as in Figure 4 calculating intersections with all triangles is very costly. To avoid this, you can subdivide the initial AABB into smaller boxes and intersect with those first. This process can be repeated until one smaller box contains the desired number of triangles. (Sebastian Lague, 2024)

A white dragon with a green laser pointing at it

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Figure : Complex mesh with BVH applied

You can think of this structure as many smaller AABBs parented to each other. First you check if you intersect with the root node (which is also the AABB). If that is the case, you evaluate its child nodes. If the child node is a leaf node the algorithm can start calculating intersections with the primitives. This approach allows you to determine the level of detail for the boxes and the minimum number of triangles per box.



Figure : Tree structure for BVH

## sphere tracing (ray marching)

### Fundamentals

#### Signed distance fields (sdf)

Another way to visualize 3D objects is by using signed distance fields (SDF).

There are 2 ways of storing SDF data. One being baked volumetric data and the other being a mathematical function. The latter is explained here after and is the one referred to when writing about SDFs.

take in a point and calculate the smallest distance from the surface of the SDF to that point. If a point is outside the surface of the SDF, the function will return a positive distance value. If it is inside the surface, it will return a negative distance value. When a point is perfectly aligned with the surface the returned value will be 0. Figure 6 is an example of what values such a function returns.



Figure : Example of SDF output

Let’s look at the simplest shape to calculate: a sphere.

A black background with white text

Description automatically generated

It takes in a point. It calculates the length to the point and subtracts the radius. If this result is negative we are inside the sphere, if it is positive we are outside the sphere. This is assuming the sphere is at position (0, 0, 0).

If you want to have translations, rotations or scaling you must manipulate the point before calculating the final value. (Quilez, n.d.)

The biggest benefit of SDFs is that they are usually fully implemented in code in the fragment shader. Meaning this requires way less memory than when compared to triangle meshes.

#### Ray marching algorithm

##### The marching loop

We need a slightly different algorithm to ray tracing, but with some similar principles. We still use a camera to cast rays through an image plane. However, we cannot calculate any intersection points due to the nature of the SDFs. The most default approach is to step forward along a ray at a fixed increment. If at any point the returned value of the SDF is negative, we can consider that we have hit an object. In Figure 7 one can see that if the increment size is too big the algorithm can easily miss a surface. However, if the step size is too small then it can cause reduced performance.

A diagram of a graph

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Figure : Ray marching basic and a missed surface

There is however a variation called sphere tracing that is more efficient and precise, presented in (Hart, 1996). The process goes as follows:

1. We can calculate the distance to the SDFs in the scene by giving passing in the origin of the ray.
2. Then we can displace the origin of the ray along its direction, using the distance value returned by the SDF.
3. Repeat steps 1 and 2 until one of 2 possible outcomes:
   1. The distance we can travel is smaller than an arbitrary value (0.001), meaning we hit an object
   2. The value of the total distance travelled by the ray has exceeded the scene boundaries.

The pseudo code

1. distance travelled = 0

2. origin = camera point

3. while (true)

4. point = origin + distance travelled \* direction

5. distance able to travel = distance to scene based on point //loops over all SDFs

6. distance travelled = total distance + distance able to travel

7. if distance able to travel < 0.001

8. break //hit object

9. if total distance > scene boundaries

10. break //no objects hit

In Figure 8 both rays are being marched towards the triangle from left to right. The top ray represents outcome ‘a’ where the SDF result approaches 0. As a result, the pixel for which this ray was cast should be colored with the triangle’s color properties. The bottom ray represents outcome ‘b’ where the distance the ray travelled exceeded the scene bounds (in this case the image bounds). (Devred, 2022)

While this approach is more memory friendly than using triangle meshes, it does mean the entire scene needs to be reconstructed every frame. And the more complex these SDFs are the more computation time they require.

A black and white drawing of a triangle

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Figure : Example of both scenarios when raymarching (Hart, 1996)

##### retrieving the distance to the scene

The main bottleneck of performance is acquiring the distance to the scene for every step of the ray. In its most primitive form of execution the pseudo code for it looks something like this.

1. minimum distance = infinity

2.

3. for object in scene

4. distance = distance to object based on point

5. if distance < minimum distance

6. minimum distance = distance

7. 4. return minimum distance

This is a heavy computation happening every frame for every ray at each step it takes. If you have a screen of 100 by 100 pixels with an average ray step of 10 to traverse the scene. You would evaluate this function 100 000 times each frame. This linearly increases with the number of objects in the scene. To speed this up can we apply the same acceleration structures commonly used for ray tracing?

### Usage

The technique has been around for a while (Wyvill & Wyvill, 1989) in different shapes. It was mostly used as baked volumetric data. Recently, GPUs were evolving their computational/ALUs abilities faster than their memory band width. This meant purely mathematical SDFs became competitive against a 3D-texture based SDF. (Quilez, n.d.)

When compared to rasterization, which consists of the vertex shader, rasterization and the fragment shader, the ray marching algorithm can be fully implemented in the fragment shader, allowing for integration with existing pipelines. Its use cases are cheap ambient occlusion, screen space reflections, rendering volumetrics, rendering clouds. (Papaioannou et al., 2010; “Ray Marching,” 2024; Schneider, 2024; Tomczak, 2012)

In Unreal Engine 5 ray marching is used for ambient occlusion and distance field shadows. (Unreal Engine 5, n.d.; Ureal Engine 5, n.d.)

There is a game called “Claybook” (<https://claybookgame.com/>) which handles the entire rendering pipeline using ray marching and fully exploiting the benefits and quirks of raymarching.

The website “shadertoy” (<https://www.shadertoy.com/>) developed by Inigo Quilez and Pol Jeremios is a tool used to teach and create demo scenes. It purely uses the ray marching algorithm. Writing code happens in GLSL.

There is also the “demoscene” community, they specialize in creating non-interactive audio-visual presentations executed in real time on computers. (“Demoscene,” 2019) Which have embraced “shadertoy” and SDFs in general for their scenes.

# Research

**In the research section, you detail the elements of your experiment(s), the tests, objects you will test upon and subjects you will test with, the data gathering, data cleaning or feature extraction, measurements, … and you present the results obtained in an objective manner for each of the tests you conducted.**

# case study

**Alternatively, as opposed to research, you might have opted for a case study. Whichever you choose, you detail the elements of your experiment(s), the tests, objects you will test upon and subjects you will test with, the data gathering, data cleaning or feature extraction, measurements, … and you present the results obtained in an objective manner for each of the tests you conducted.**

# Discussion

**In this section, you offer an interpretation of the results you obtained and try to relate them to the theoretical framework you presented. This is typically not a very long section, but obviously one of the most important ones.**

# Conclusion

**In this section, you ascertain the demonstrable outcomes of your study and outline the merits of the project for the academic field and the discourse community. This is typically not a very long section, but obviously also one of the more important ones.**

# Future work

**This section is sometimes standalone, sometimes incorporated in the conclusion. It looks at the shortcomings of the study, alternative strategies, and what could be the next course of action in the research field. This is typically not a very long section.**

# Critical Reflection

**This section is typically associated with a bachelor paper, not other forms of serious writing. It allows the student to reflect on the learning outcomes, both academically and in terms of personal growth.**

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# Acknowledgements

**In this section, you can thank people who contributed to your work in a meaningful way.**

# Appendices

**In many cases, there are items that were developed for a research paper that can’t go into the actual paper in full. Things suc as code, art pieces, output of statistical analysis, questionnaires, … In this section, you can present these elements; use the first page to list and number the items, then paste them sequentially. If some items are too large, you can store them online, and link to them. Common practice is to keep those links active at least one year after the publication of the thesis.**