FAST GPU GENERATION OF DISTANCE FIELDS FROM A VOXEL GRID

by

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I declare that this dissertation is my own work and that the work of others is acknowledged and indicated by explicit references.

Nicolas Fedor
May 2025

Abstract

Write a summary of the work presented in your dissertation. Introduce the topic and highlight your main contributions and results. The abstract should be comprehensible on its own, and should no contain any references. As far as possible, limit the use of jargon and abbreviations, to make the abstract readable by non-specialists in your area. Do not exceed 300 words.

Acknowledgements

Write any personal words of thanks here. Typically, this space is used to thank your supervisor for their guidance, as well as anyone else who has supported the completion of this dissertation, for example by discussing results and their interpretation or reviewing write ups. It is also usual to acknowledge any financial support received in relation to this work.

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Glossary

P	Placeholder

Abbreviations

SVO	Sparse Voxel Octree
JFA	Jump Flooding Algorithm
CPU	Central Processing Unit
GPU	Graphics Processing Unit
DAG	Directed Acyclic Graphs
SVDAG	Sparse Voxel Directed Acyclic Graph

Chapter 1

Introduction

In recent years, real-time computer graphics applications have increasingly adopted distance fields as a fundamental representation for rendering and physics simulations (Jones & Satherley 2001). Distance fields, which encode the minimum distance from any point to the nearest surface, provide an elegant solution for various graphics operations including collision detection (Fuhrmann, Sobotka & Groß 2003), soft shadows (Tan, Chua, Koh & Bhojan 2022), and ambient occlusion (Wright 2015). While techniques exist for generating distance fields in real-time from a triangle mesh (Kramer 2015), techniques covering distance field generation from discrete voxel data are uncommon.

1.1 Problem Statement

Current approaches to distance field generation from voxel grids present various tradeoffs that limit their effectiveness in dynamic scenes. The Jump Flooding Algorithm (JFA) (Rong & Tan 2006, Rong & Tan 2007, Wang, Ino & Ke 2023), while efficient for parallel computation, introduces accuracy issues particularly at larger distances from surfaces and near feature edges. Scan, or prefix sum-based, approaches (Erleben & Dohlmann 2008) provide accurate results but suffer from inherent sequential dependencies that limit GPU parallelization. Wavefront propagation methods can efficiently update local regions but may struggle with concurrent updates in complex scenes (Teodoro, Pan, Kurc, Kong, Cooper & Saltz 2013).

Common optimization strategies, such as spatial partitioning into smaller chunks for localized updates (Naylor 1992), introduce their own challenges including boundary artifacts and increased

memory management overhead. While these techniques work well in isolation for specific use cases, there remains a fundamental gap in solutions that can handle arbitrary dynamic scene modifications while maintaining both accuracy and performance. This research investigates whether a novel hybrid approach—combining elements of existing techniques or developing new algorithmic patterns—could better address these challenges.

1.2 Aims and Objectives

This research aims to develop and evaluate novel GPU-based techniques for rapid distance field generation from voxel grid representations. The primary objectives are:

- To analyze and classify existing approaches to distance field generation, with particular focus on GPU-accelerated methods.
- To develop new algorithms that optimize the conversion process from voxel grids to distance fields.
- To implement and validate these algorithms on modern GPU architectures.
- To establish a comprehensive comparison framework for evaluating different distance field generation techniques.

1.2.1 Performance Metrics

The evaluation of the proposed methods will be conducted against sparse voxel octree implementations, which currently represent the state-of-the-art in many graphics applications. Key performance metrics include:

1. Computation time for initial distance field generation.
2. Memory consumption during generation and storage.
3. Update latency for localized geometric changes.
4. Scalability with increasing voxel grid resolution.
5. Accuracy of distance field values compared to analytical solutions.
6. GPU resource utilization, including memory bandwidth and compute occupancy.

1.3 Scope and Limitations

While this research addresses the core challenge of distance field generation, several related aspects fall outside its scope:

- The optimization of ray marching techniques for distance field rendering.
- The development of new compression methods for distance field storage.
- The optimization of the underlying renderer, which will include features like:
  - Memory management between the CPU and GPU.
  - Sychronization with the windowing framework.
  - Optimizing presentation of ray marching output image.

The focus remains specifically on the GPU-based generation process and its performance characteristics in dynamic scenarios. The research assumes access to modern GPU hardware and primarily targets real-time graphics applications where frequent distance field updates are required.

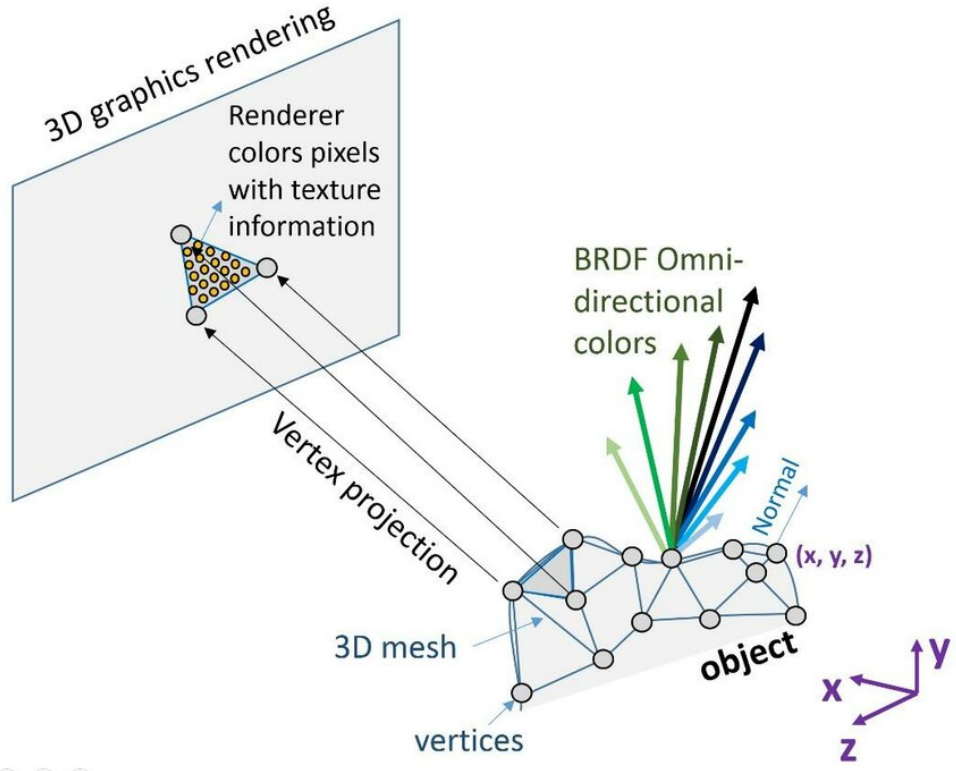
A sample "Falling Sand" graphics application will be implemented that will serve as a demo and benchmark for real-time performance of the distance field regeneration. The simulation itself will not be optimized and include a bare minimum of sand and water voxels that can fall and spread out in the world.

Chapter 2

Literature Review

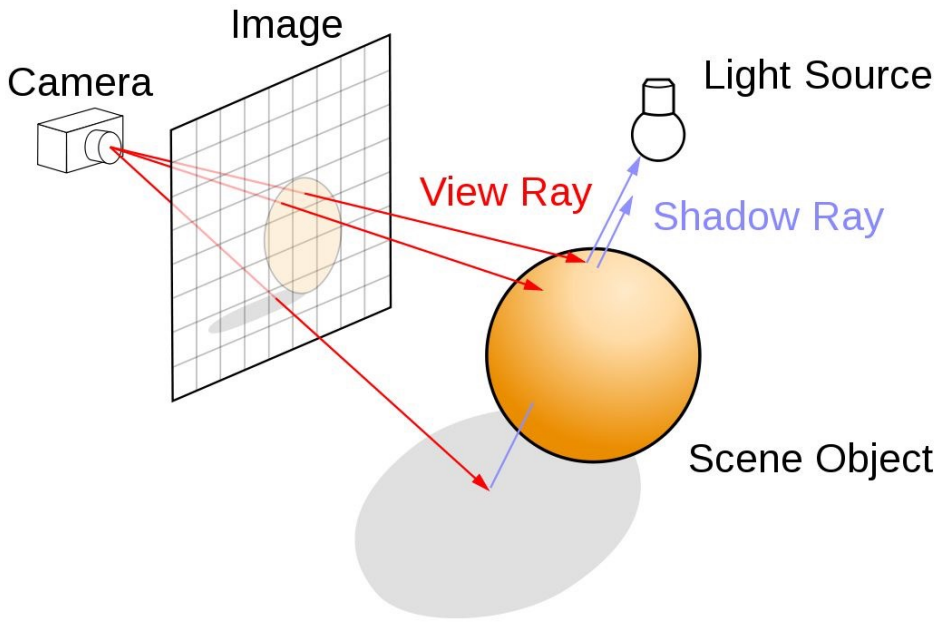
Traditional real-time rendering has predominantly relied on triangle meshes as the fundamental primitive, with modern graphics hardware specifically optimized for rasterizing triangles efficiently (Akenine-Moller, Haines & Hoffman 2019).

Figure 2.1: Illustration of how a collection of triangles get rasterized onto a screen as demonstrated by Lafruit et. al 2016



While this approach remains widespread, recent advances in hardware-accelerated ray tracing, particularly with NVIDIA's RTX series (2018) and AMD's RDNA2 architecture (2020), have enabled real-time ray tracing in commercial applications. Games like "Cyberpunk 2077" and "Metro Exodus Enhanced Edition" demonstrate that hybrid approaches combining rasterization and ray tracing can achieve photorealistic effects such as global illumination and accurate reflections at interactive framerates (Keller, Viitanen, Barré-Brisebois, Schied & McGuire 2019). However, both rasterization and ray tracing face similar challenges when representing highly detailed or volumetric content, leading to the exploration of alternative representations.

Figure 2.2: Visualisation of how ray-casting is used to rasterize a 3D world. Source: Wikipedia



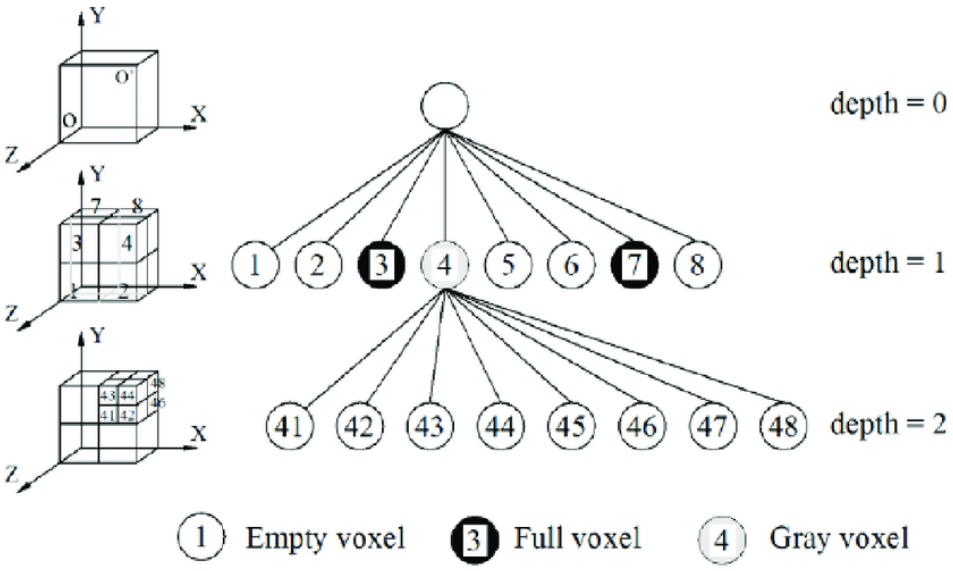
2.1 Voxel-Based Representations and Optimization

2.1.1 Sparse Voxel Octrees

Sparse Voxel Octrees (SVOs) have emerged as a powerful solution for managing large-scale voxel worlds (Crassin, Neyret, Lefebvre & Eisemann 2009). Crassin et al. (2009) introduced GigaVoxels, a groundbreaking approach that demonstrated efficient rendering of highly detailed voxel scenes through hierarchical structure and streaming. Their work showed that SVOs could effectively compress empty space while maintaining quick traversal times for ray casting. Building

on this foundation, Laine and Karras (2010) developed an efficient sparse voxel octree (Laine & Karras 2010) implementation that improved upon previous approaches by introducing a novel node structure and traversal algorithm. Their method significantly reduced memory requirements while maintaining high rendering performance, making it particularly suitable for static scenes with complex geometry.

Figure 2.3: Illustration of the structure of a Sparse Voxel Octree, nodes with more details have additional subdivisions. (Truong-Hong & Laefer 2014)



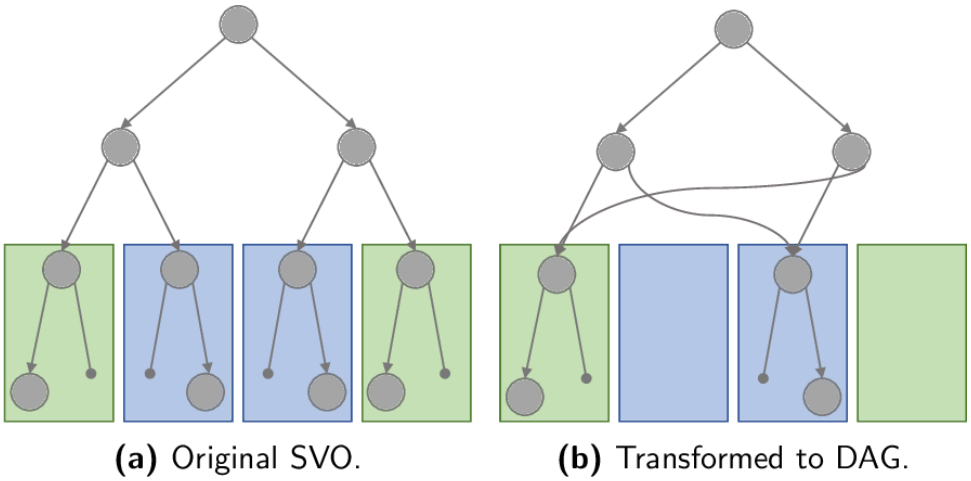
2.1.2 Compression and Optimization Techniques

Several researchers have explored various compression techniques to further optimize voxel storage. Kämpe et al. (2013) introduced directed acyclic graphs (DAGs) for voxel scenes (Kämpe, Sintorn & Assarsson 2013), achieving compression ratios of up to 50:1 compared to standard SVOs while maintaining real-time rendering capabilities. This approach proved particularly effective for architectural and synthetic scenes with repeated structures.

2.1.3 Challenges in Dynamic Scenes

The primary challenge in dynamic voxel environments lies in maintaining data structures that can efficiently support modifications. Updating traditional SVOs in real-time presents significant

Figure 2.4: Comparison of a octree versus the compressed format of a SVDAG, illustrated as a quad tree for brevity. (Dolonius 2018)



computational overhead, as changes often require rebuilding portions of the tree structure. Pan (2021) explored a novel technique for merging SVOs and dynamically creating nodes where updates are needed (Pan 2021), while this showcases SVOs have the potential to support large dynamic scenes, the results show that real-time updates, such as in a video game application, are hard to achieve.

2.2 Distance Fields as an Alternative Representation

Distance fields have gained attention as an alternative to direct voxel storage, offering several advantages for both rendering and collision detection. Several recent works have demonstrated the advantages of using distance fields for real-time rendering of implicit surfaces (Hadji-Kyriacou & Arandjelović 2021) and function grids (Söderlund, Evans & Akenine-Möller 2022).

2.2.1 Real-Time Generation and Updates

The challenge of generating and updating distance fields in real-time remains an active area of research. Techniques such as Jump Flooding (Rong and Tan, 2006) provide fast approximate solutions but suffer from accuracy issues (Rong & Tan 2006, Rong & Tan 2007); improvements to Jump Flooding are being researched that allow for it to be used in dynamic contexts where recalculation of distance fields is needed (Stevenson & Navarro 2022).

Figure 2.5: Illustration of a discrete signed distance field grid. Negatives values indicate a cell inside the shape, positive values indicate a cell outside of the shape.

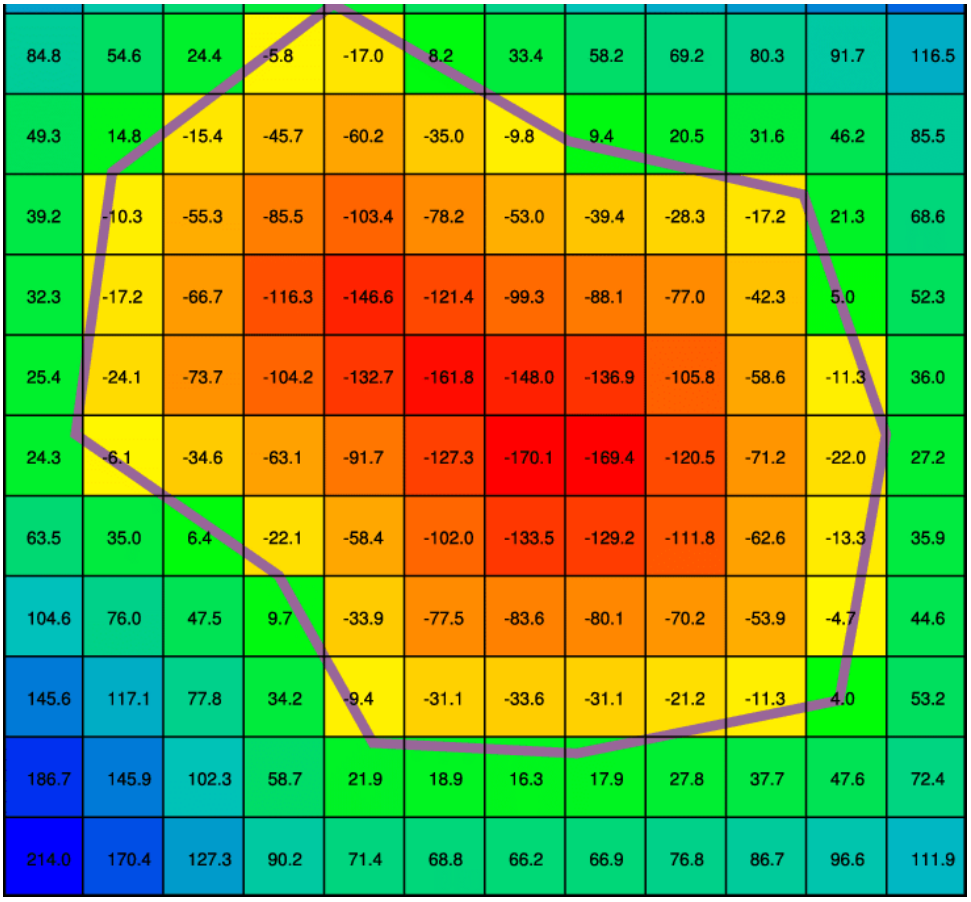
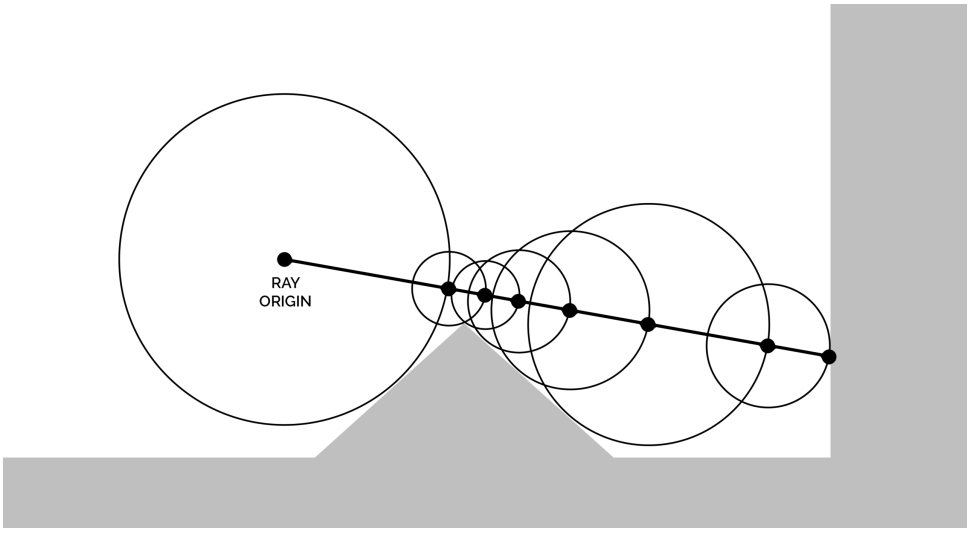


Figure 2.6: Example of a ray marching from a camera using sphere ray marching and a signed distance function. The ray will query the function for the distance to the nearest object, and advance by that amount.



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