Procedural Creation of Atmospheric Effects for Information Systems using CUDA

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Abstract

This paper presents a Design Science Research (DSR) approach to addressing visualization bottlenecks in environmental Information Systems Development (ISD). By developing a CUDA-based atmospheric effects framework utilizing the Material Point Method (MPM) and Marching Cubes algorithms, we demonstrate how GPU acceleration transforms ISD methodologies for data-intensive decision support systems (DSS). This research contributes to digital transformation of environmental monitoring platforms by enabling real-time processing of complex simulation data that traditionally require significant computational resources. The prototype demonstrates scalable performance handling up to 6.5 million particles while enabling configuration-driven customization that allows information systems developers to integrate sophisticated environmental visualization without specialized graphics expertise. This approach democratizes atmospheric data visualization for environmental monitoring systems. Empirical results demonstrate real-time visualization capabilities suitable for operational deployment.

Keywords: Environmental DSS, GPU-Accelerated ISD, Procedural Modeling, Particle Systems.

1. Introduction

Information systems supporting environmental monitoring increasingly require sophisticated real-time data visualization capabilities. Recent parallel computing advancements enable IS developers to incorporate advanced visualization techniques without specialized graphics expertise, democratizing access to complex environmental simulations. This research demonstrates how CUDA-based environmental effect simulation transforms decision support systems for climate and environmental data.

1.1. Research objectives

This research adopts a design science research methodology to integrate computational science capabilities with practical ISD requirements [11, 12], addressing challenges in enterprise-scale environmental monitoring systems [13, 7]. We pose the central research question: how can

GPU-based parallelization methods be integrated into ISD processes to optimize simulation performance and democratize visualization capabilities in environmental DSS? We hypothesize that CUDA-based MPM implementation can achieve real-time performance benchmarks suitable for ISD deployment (<60 s per frame for enterprise-scale datasets).

2. Related work

Recent advances in procedural atmospheric modeling focus on real-time performance suitable for information systems applications. Cortial et al. developed multi-genre cloud models using complex noise functions [1], while García-Dorado et al. integrated weather simulation into urban procedural modeling [4]. These approaches demonstrate the feasibility of incorporating sophisticated environmental effects into interactive systems, supporting our ISD-focused implementation.

2.1. Technical background

Material Point Method (MPM) offers distinct advantages in simulating complex materials like snow by combining Lagrangian particles with Eulerian grids, enabling efficient handling of topological changes without mesh connectivity issues [14]. MPM generalizes Particle-In-Cell (PIC) and Fluid Implicit Particle (FLIP) methods to solid mechanics, crucial for environmental simulations in information systems [16]. For collision detection, Signed Distance Functions (SDF) provide robust implicit surface representation, enabling efficient computation of minimum distances between objects [9]. The Marching Cubes algorithm generates high-resolution surfaces from volumetric data, essential for real-time visualization in decision support systems [8].

3. Procedural generation of particles using MPM and Marching Cubes

The workflow combines MPM simulation with Marching Cubes surface extraction (Fig. 1). Object deformation follows conservation principles expressed as:

$$\frac{D\rho}{Dt} = 0, \quad \rho\frac{Du}{Dt} = \nabla \cdot \sigma + \rho g, \quad \sigma = \frac{1}{J}\frac{\partial \Psi}{\partial F_{\mathrm{E}}}F_{\mathrm{E}}^{\mathrm{T}}, \tag{1}$$

where ρ is density, t time, u velocity, σ Cauchy stress, g gravity, Ψ is a density of elastic-plastic energy, F_E shows elastic part of the deformation gradient F, J is determinant of F.

3.1. CUDA-Parallelized MPM Implementation

The GPU implementation addresses data-intensive environmental dataset processing within operational constraints, achieving 30-second frame rates for 1.4M particle simulations (Tab. 1). For parallel execution on the GPU, a fixed thread block size of 512 threads per bloc is employed. Key algorithmic steps include:

Particle-to-Grid Transfer: Mass and velocity interpolation using B-spline functions with a scatter strategy, where each particle distributes its data to nearby grid nodes.

Grid Updates: Velocity is updated based on conservation equations considering gravitational forces and boundary collisions detected via Signed Distance Functions.

Grid-to-Particle Transfer: Combined PIC-FLIP velocity update maintaining numerical stability through CFL condition.

Detailed mathematical formulations are provided in Appendix A, available at `link.pg.edu.pl/proc-effects-3d-cuda_AppendixA`.

3.2. ISD Pipeline Architecture

Figure 2 illustrates the proposed integration architecture for CUDA-based atmospheric effects within standard ISD infrastructure. This layered architecture follows established ISD patterns [7], enabling seamless integration with existing information systems while maintaining separation of concerns between presentation, service, processing, and data layers [13].

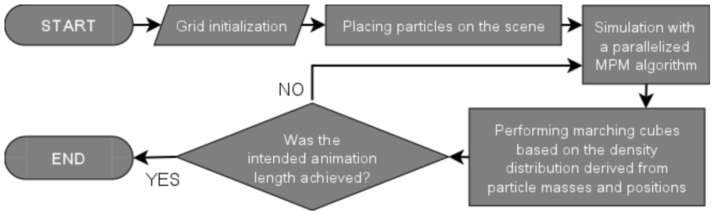

Fig. 1. Block diagram of mesh generation part of the algorithm

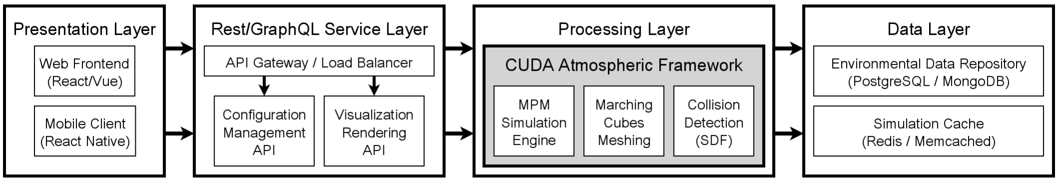

Fig. 2. Example of CUDA atmospheric effects integration within ISD architecture

4. Results

CUDA-parallelized MPM successfully handles simulations up to 6.5 million particles, demonstrating enterprise-level scalability [5, 2]. Table 1 demonstrates scalability across particle densities (4.5×10^5 to 6.5×10^6), validating real-time performance for ISD deployment. Collision dynamics (Fig. 3 A-B) and adhesion modeling (Fig. 3 C-D) provide templates for supply chain and smart city infrastructure applications [10, 15].

5. Discussion and Conclusions

Empirical validation demonstrates 3-5× performance improvements across test configurations compared to the results in [14], confirming our hypothesis that CUDA-based MPM achieves real-time benchmarks suitable for ISD deployment. The framework directly addresses the research question by democratizing atmospheric visualization access for IS developers through open-source implementation and configuration-driven customization.

Memory-intensive Marching Cubes presents scalability challenges for larger simulations, indicating future optimization needs. However, results demonstrate algorithmic potential for enterprise-scale environmental monitoring systems requiring real-time feedback loops.

5.1. Prospective applications and future research

Future work will integrate this framework with geospatial information systems through OpenGeoSpatial Consortium standards, enabling applications in flood prediction and climate resilience planning [3]. Memory optimization for edge computing deployment and adaptive mesh techniques will enhance scalability for IoT-enabled field devices [6].

Table 1. Particle counts, grid sizes, and frame times for ISD deployment.

Particle count	Grid resolution	Time per frame	CPU & GPU config.	ISD applicability
3.0×10^5	$125 \times 125 \times 125$	10 seconds	i7-8750H, GTX1050Ti	real-time
4.5×10^5	$140 \times 140 \times 140$	7 seconds	i7-9700K, RTX4070	decision support
4.5×10^5	$140 \times 140 \times 140$	32 seconds	i7-8750H, GTX1050Ti	Near real-time
1.4×10^6	$210 \times 210 \times 210$	30 seconds	i7-9700K, RTX4070	analysis
1.4×10^6	$210 \times 210 \times 210$	261 seconds	i7-8750H, GTX1050Ti	Batch
3.4×10^6	$280 \times 280 \times 280$	293 seconds	i7-9700K, RTX4070	processing
6.5×10^6	$350 \times 350 \times 350$	701 seconds	i7-9700K, RTX4070	High-fidelity sim

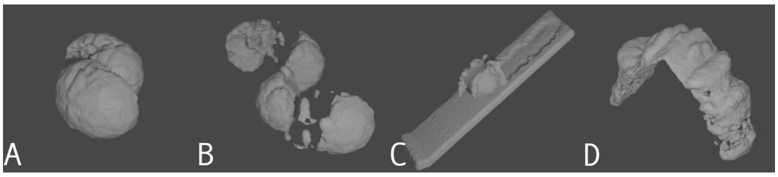

Fig. 3. A: Simulation of non-coaxial snowball collisions shows impact physics. B: After several frames, simulation shows collision breaking into pieces. C: Simulation shows snowball rolling downhill, gaining snow realistically. D: Simulation shows physics of falling snow from obstacle.

6. Summary

This research presents a CUDA-accelerated solution for procedural generation of atmospheric effects in 3D scenes, introducing a novel approach that bridges computational science and IS visualization needs. The system combines the Material Point Method (MPM) with Marching Cubes to create realistic weather phenomena, demonstrating effective integration of visualization technologies into information systems development. Results show significant GPU performance improvements, enabling simulations with up to 6.5 million particles while maintaining visual quality—addressing key challenges in information systems requiring real-time data processing.

The study's main contribution lies in its efficient parallelization strategy and novel scatter approach for particle-grid data transfer, establishing new patterns for integrating complex computational models into IS workflows. This approach aligns with empowering interdisciplinary roles in ISD by making specialized computational techniques accessible to IS developers. While achieving impressive physics simulation and visual realism results, the implementation revealed memory constraints when using Marching Cubes for large-scale simulations. Future research should focus on memory optimization and adaptive mesh techniques to enhance scalability, exploring how data science and AI techniques might optimize these computational models for broader information systems applications.

The source code used in this study is available at `link.pg.edu.pl/proc-effects-3d-cuda`.

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