

Open source time domain simulations using parallelized
computing on consumer hardware.

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Abstract

With serious competition in the modern market it is not trivial to create a product that can match the expectations of professional users and still appeal to hobby engineers, especially at a modest price point. The gap in capabilities between enterprise and open source simulation software is growing bigger due to lack of funding, which often results in limited research and development for open source projects. This growing disparity poses a significant challenge for developers aiming to balance advanced features with affordability. Striking a harmony between meeting the rigorous demands of professionals while remaining accessible to enthusiasts is a complex task.

Enterprise simulation software benefits from substantial financial backing, enabling teams to invest in cutting-edge research, continuous enhancements, and dedicated customer support. This translates to robust features, high accuracy, and comprehensive technical support, making them the preferred choice for intricate and mission-critical projects. However, the cost associated with these solutions can be prohibitive for smaller businesses and individual hobbyists. This gap is further exacerbated by the intricate nature of simulation software. Meeting the needs of professionals frequently involves complex algorithms, intricate modeling, and high-performance computing. Striving to offer similar capabilities within a modest price range for hobbyists can be daunting, as the associated costs can quickly spiral upwards.

This paper presents a proof-of-concept software project that aims to illustrate the potential of open source magnetic field simulations utilizing parallelized computing techniques on consumer-grade hardware. Magnetic field simulations hold immense significance across scientific, engineering, and technological domains, yet their resource-intensive nature often limits accessibility, particularly in the context of proprietary software and high-cost hardware. By conducting a thorough analysis of existing open source simulation tools, parallel computing frameworks, and optimization strategies, we lay the groundwork for a proof-of-concept that showcases the potential of democratizing magnetic field simulations. This paper provides an in-depth exposition of the technical underpinnings involved in parallelization implementation, optimization techniques, and comprehensive performance evaluations. Through our preliminary experimentation, we offer empirical evidence of substantial reductions in simulation runtime while maintaining accuracy levels comparable to established proprietary solutions.

Moreover, the paper acknowledges and addresses the inherent challenges intrinsic to parallel programming, hardware limitations, and scalability concerns when deploying simulations on consumer-grade hardware. By providing practical insights and strategic recommendations, we outline potential avenues to navigate these challenges and attain optimal performance across varying hardware configurations.

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1 Introduction

1.1 Introduction to Computational Electromagnetics

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4 User Experience

4.1 Workspaces

5 Modularity

5.1 Overview of the Magisim model

5.2 Extensions

6 The simulator

6.1 Introduction

6.2 Maxwell's Equations

Maxwell's equations are a fundamental set of equations in the field of electromagnetism, providing the mathematical framework for understanding the behavior of electric and magnetic fields in space and time. In the context of computational electromagnetics, Maxwell's equations serve as the foundational principles upon which electromagnetic simulations, including magnetic field simulations, are based.

Maxwell's equations consist of four essential equations that relate electric and magnetic fields to their sources (charges and currents). These equations can be expressed as follows:

1. **Gauss's Law for Electricity (Coulomb's Law):**

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$$

Here, $\nabla \cdot \mathbf{E}$ represents the divergence of the electric field, and ϵ_0 is the permittivity of free space.

2. **Gauss's Law for Magnetism:**

$$\nabla \cdot \mathbf{B} = 0$$

This equation states that magnetic field lines are always closed loops and that there are no magnetic monopoles.

3. **Faraday's Law of Electromagnetic Induction:**

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

It describes how a changing magnetic field induces an electromotive force (EMF).

4. **Ampère's Circuital Law with Maxwell's Addition:**

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

This equation relates the circulation of the magnetic field ($\oint \mathbf{B} \cdot d\mathbf{l}$) to the electric current (I) and the rate of change of electric flux ($\partial \mathbf{E} / \partial t$).

Maxwell's equations provide the theoretical foundation for magnetic field simulations. These equations allow scientists and engineers to mathematically describe and predict the behavior of electromagnetic fields, including magnetic fields, in various scenarios. Computational electromagnetics leverages numerical methods and simulation techniques to solve these equations in complex, real-world situations.

6.3 FDTD: Applying Maxwell's Equations in the Time Domain

The Finite-Difference Time-Domain (FDTD) method is a powerful numerical technique used to solve Maxwell's equations in the time domain. It is a fundamental approach in computational electromagnetics, allowing for the simulation of electromagnetic wave propagation, interactions with materials, and the prediction of complex electromagnetic phenomena.

Overview of the FDTD Method

The FDTD method discretizes both time and space, allowing for the direct integration of Maxwell's equations in their time-domain form. This discretization divides the simulation domain into a grid of discrete points in both space and time. At each grid point, electromagnetic field values (electric and magnetic fields) are computed iteratively, advancing in discrete time steps.

Time-Stepping Scheme

In the FDTD method, the update of electromagnetic field components at each grid point follows a time-stepping scheme. The update equations are based on the finite-difference approximations of Maxwell's equations. For example, the update equations for the electric field (E) and magnetic field (H) components in 3D space can be expressed as:

For the electric field:

$$E_x^{n+1}(i, j, k) = E_x^n(i, j, k) + \frac{\Delta t}{\varepsilon(i, j, k)} (\nabla \times H)_x^n(i, j, k)$$

and similarly for E_y and E_z

For the magnetic field:

$$H_x^{n+1}(i, j, k) = H_x^n(i, j, k) + \frac{\Delta t}{\mu(i, j, k)} (\nabla \times E)_x^n(i, j, k)$$

and similarly for H_y and H_z

Here, n represents the time step, Δt is the time step size, and ε and μ are the permittivity and permeability of the material at the grid point (i, j, k) .

Significance in Magnetic Field Simulations

The FDTD method is particularly significant in magnetic field simulations due to its ability to capture complex temporal behaviors of electromagnetic phenomena. It allows researchers and engineers to study magnetic field interactions with materials, structures, and devices over time. This is crucial in applications such as:

- Magnetic resonance imaging (MRI)
- Magnetic shielding design
- Electromagnetic compatibility (EMC) analysis
- Magnetic field exposure assessment
- Magnetic field sensor development

By directly applying Maxwell's equations in the time domain, the FDTD method provides a comprehensive understanding of the dynamic behavior of magnetic fields, making it an indispensable tool in computational electromagnetics.

Parallelization and FDTD

In the context of your paper, parallelized computing techniques play a vital role in accelerating FDTD-based magnetic field simulations. Parallelization allows for the simultaneous computation of field values at multiple grid points, reducing simulation runtimes and enabling the efficient exploration of complex electromagnetic scenarios. The combination of FDTD and parallelization exemplifies how computational techniques can bridge the gap between advanced electromagnetic research and accessible, consumer-grade hardware.

The next sections of this paper delve into the application of parallelized computing techniques within the FDTD framework, providing insights into optimizing magnetic field simulations for various hardware configurations.

6.4 The compromise between accuracy and speed

6.5 Computation

6.5.1 Introduction to parallel computing

A regular computer usually performs tasks serially, one operation at a time. While this might be the most efficient method for everyday tasks, it does not apply to computationally heavy tasks spanning multiple dimensions or matrix operations. This has largely been solved today thanks to the GPU (Graphics Processing Unit) or graphics card as it is more commonly referred to as.

6.5.2 The application of parallel computation in time domain field simulations

Computation is a critical aspect of time domain field simulations. These simulations involve solving complex differential mathematical models and processing large datasets, which can be extremely computationally demanding. The traditional serial computing approach is therefore insufficient for handling the computational complexity associated with magnetic field simulations.

To address these challenges, we turn to parallelization, a technique that enables concurrent execution of computations across multiple processors or cores. Modern GPUs, designed for parallel processing, have become instrumental in accelerating computational tasks, including solving differential equations, a core component of time domain magnetic field simulations

According to Moore's Law, the amount of transistors in a given area of microchips are doubled every year.

With parallelization, the effectiveness of a computational can be increased drastically, essentially allowing for $n - 1$ dimensional computation as illustrated in the below visualizations.

7 Visualization