A High-Performance Hybrid Parallel Framework for Electromagnetic Analysis Using MPI and CUDA

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ABSTRACT

Electromagnetic (EM) analysis is fundamental in many engineering applications, including antenna design, microwave circuits, and radar systems. Among various numerical methods, the finite element method (FEM) is widely used for its ability to handle complex geometries and material inhomogeneity. However, large-scale three-dimensional EM simulations with millions of degrees of freedom (DoFs) require solving complex-valued sparse systems, leading to substantial computational demands. In this study, the scattering of a dielectric-coated perfect electric conductor (PEC) is analyzed using the vector wave equation derived from Maxwell's equations, and the Finite Element Tearing and Interconnecting Dual–Primal (FETI-DP) method [1] is employed to efficiently solve the resulting large-scale system through domain decomposition. To further enhance performance and scalability, a hybrid parallel framework combining MPI-based distributed computing with GPU acceleration is developed and applied to the FETI-DP solver.

To develop an efficient solver based on the FETI-DP algorithm, this study presents a high-performance hybrid parallel framework combining MPI and CUDA (MPI–CUDA Hybrid Parallel Framework). The computational domain is decomposed into multiple subdomains, each assigned to an MPI process. Each process performs local computations and exchanges interface data with neighboring subdomains via the MPI. Within each process, computationally intensive tasks—such as complex matrix–vector multiplications and iterative solver operations—are offloaded to GPUs, enabling massive data-parallel acceleration. In this heterogeneous hybrid architecture, CPUs handle global control and inter-process communication, while GPUs perform local numerical computations using CUDA libraries. This structure achieves high computational efficiency and scalability, significantly reducing total execution time compared to CPU-only implementations.

The numerical results demonstrate that the proposed hybrid solver significantly improves computational efficiency and scalability, making it suitable for large-scale three-dimensional electromagnetic analyses.

REFERENCES

1. Zhang, K., and Jin, J.-M., "Parallel FETI-DP algorithm for efficient simulation of large-scale EM problems," *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields*, Vol. 29, No. 5, 2016, pp. 897–914.