Extreme Fidelity Computational Electromagnetic Analysis in the Supercomputer Era

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***Abstract*—Ever-increasing fidelity and accuracy needs for advanced electromagnetic applications have pushed problem sizes towards extreme scales. It puts a high premium on parallel and scalable algorithms with optimal computational complexity. We investigate high-performance, geometry-aware integral equation domain decomposition (DD) methods for the solution of time-harmonic Maxwell's Equations. The technical ingredients include a volume-based optimized local multi-trace integral equation formulation, and a surface-based interior penalty discontinuous Galerkin formulation. The work has three major benefits: (i) it results in a robust, cost-effective preconditioning technique that reduces the condition number of very large systems of equations; (ii) it provides a flexible and natural way to set up the mathematical models, to create the problem geometries and to discretize the computational domain; (iii) it leads to massively parallel and highly scalable algorithms to reduce the time complexity of very-large scale simulations. The capability of the algorithms is illustrated through real-world applications on high-performance computing systems.**

Keywords—domain decomposition methods, discontinuous Galkerin formulation, preconditioning, high performance computing

I. INTRODUCTION

The computer simulation of electromagnetic (EM) phenomena has emerged as a powerful and indispensable tool in both the design and analysis stages of many engineering applications. In the time-harmonic regime, integral equation (IE) methods are widely used for such simulations. Applications range from advanced antenna design [1], [2], stealth technologies [3], [4], integrated circuits [5] to optics and photonics [6]. Nowadays, increasing demands are placed on enhancements of the model fidelity and improvements of the simulation accuracy [7]. Despite their apparent importance for simulation-based engineering, high-fidelity modeling and high-resolution computing present significant mathematical and computational challenges in existing IE solvers due to the growing sophistication in real-world EM applications.

One representative EM application considered is simulation-aided design of composite unmanned aerial vehicle (UAV), as illustrated in Fig. 1. Multi-layer EM absorbers [8], frequency selective surfaces [9], impedance surfaces [10] and magnetic absorbing materials are often integrated in order to reduce its radar signature. Such a high-fidelity and large-scale EM problem is very challenging and is possibly beyond the capabilities of conventional methods. The fundamental computational challenges arise from geometrical complexity in the underlying structures, from the intricacies of material properties, and from engineering design aspects (reconfigurable modeling, timely decision making, etc.).

On the other hand, high-performance computing (HPC) architectures are rapidly evolving. With the advancements of massively parallel supercomputers [11] and the flexible and general-purpose families of multi-core processors [12], the era of exascale computing is on the horizon. Many of the currently used fast algorithms become uncompetitive when mapped onto these latest HPC architectures. Therefore, it is of paramount importance to develop highly scalable computational algorithms to address these challenging high-fidelity EM problems effectively. Furthermore, to fully exploit the potential of exascale computing, CAD model preparation, mesh generation, preconditioning, solution and post-processing, all elements involved in modeling and simulation process must be in close alignment with the advancements of HPC systems.

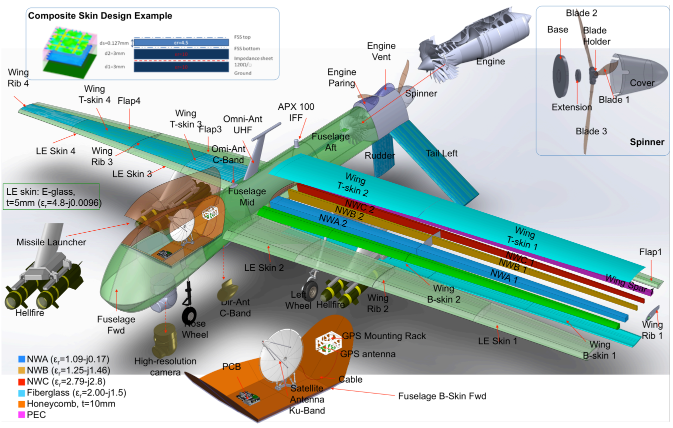

Fig. 1 A full-scale prototype of composite UAV

This research concerns the use of domain decomposition (DD) methods for the IE based solution of large, complex EM applications. DD methods have attracted considerable attention for solving partial differential equations [2], [13]–[17]. Recently, they have also been extended to IE methods [4], [5], [18]–[21]. This work aims to investigate high-fidelity and high-performance IE solvers for time-harmonic Maxwell

Equations, whose simulation capability and modeling fidelity scale with the exponential growth in computing power. The mathematical ingredients include: a surface-based IE DD method using the interior penalty discontinuous Galerkin boundary element formulation [22], and a volume-based IE DD method via the well-conditioned local multi-trace IE formulation.

Comparing to previous methods, the primary contributions are twofold: (1) the work leads to scalable convergence in DD iterations for complex composite objects using a one- level additive Schwarz preconditioner, which results in highly efficient and naturally parallelizable computational algorithms on distributed memory many-core parallel computing systems; (2) the work employs a non-overlapping geometry- aware DD method to conquer the geometric complexity of physical domains, and to resolve the intricacy of materials in sophisticated EM engineering products. It enables component oriented optimization discretization and simulation, and automating assembly of multiple components to obtain the virtual prototyping of entire product.

The mathematical advancements of the proposed work enable an adaptive, parallel and scalable SIE-based analysis framework well-suited for advanced distributed computing systems. The basic units of the parallel analysis framework consist of pre-processing, parallel computing and post-processing, all of which are formulated with proposed mathematical ingredients towards scalable parallelism. This section provides an overview of the parallel implementation of the proposed algorithms. The major steps of the parallel computing methodology can be described in Fig. 2.

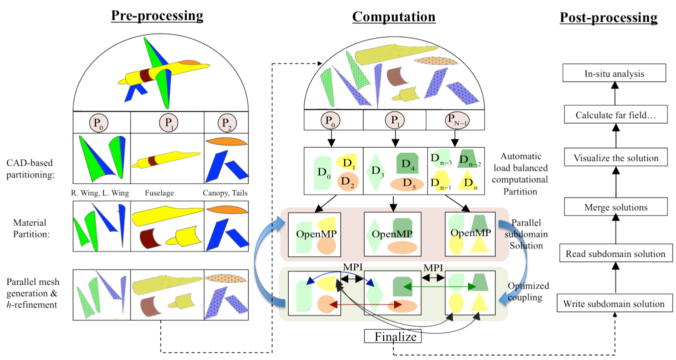

Fig. 2 Overview of the parallel computing methodology

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