Guest Editorial
Frontiers in Computational Electromagnetics

I. INTRODUCTION

COMPUTATIONAL electromagnetics (CEM) seeks numerical solutions to practical engineering problems involving electromagnetic fields and waves and their interactions with materials and designed structures and systems. While physical measurement of electromagnetic fields is often expensive and impractical, CEM develops cost-effective and efficient simulation tools to analyze, design, and optimize real-world devices, structures, and systems. Advancements in CEM rely on those in mathematical representation of physical problems, numerical foundations of methods and algorithms, and computing hardware and software infrastructure. Indeed, CEM research and practice demand the seamless but also the most advanced combination of advancements in engineering, physics, mathematics, and computer science, holding immense potential for transformative impact. CEM is one of the most challenging areas of computational science and engineering due to the inherent complexity of electromagnetic problems. Unlike problems in other disciplines, electromagnetic problems are truly 3-D, volumetric, and vector-based and involve radiation and interaction at a distance.

Electromagnetics-related technologies are becoming increasingly sophisticated and powerful, enabling rapid development of innovative applications in the fields of antennas, propagation, microelectronics, and lightwave. The importance of CEM to these technologies and applications can hardly be overstated. Nowadays, electromagnetic simulations are effectively used at frequencies spanning dc to optics, for scales ranging from subatomic to intergalactic, and in a variety of applications changing from design of antennas and RF/microwave/terahertz devices, components, and circuits to electromagnetic scattering, indoor and outdoor radio propagation, remote sensing, packaging, shielding, electromagnetic compatibility, RF interference, signal integrity, and high-speed electronics.

To address the challenges of ever-increasing problem size and complexity, as well as the diversity of applications and modeling requirements, a range of electromagnetic simulation strategies and numerical discretization techniques are essential, with no single approach being universally optimal. The paramount requirement for a CEM method and its corresponding computer program (code) is to provide accurate and reliable solutions within a reasonable execution time and memory footprint for a specified range of problems and applications, i.e., types of electromagnetic structures and their geometries, materials, and electrical sizes. For many applications, a CEM modeling technique must be a true design and optimization tool, with efficiency that enables its use as an analysis engine in electromagnetic optimizers, e.g., those based on genetic algorithm or machine learning, where thousands of analysis cycles are needed in an optimization procedure. In all cases, today's antenna, propagation, and electromagnetics researchers and practitioners expect CEM techniques to be easily and confidently used as analysis, synthesis, and design tools providing realistic, accurate, and versatile modeling of practical problems and efficient, robust, and reliable solutions with meaningful computing resources. They expect CEM to replace or complement expensive and time-consuming fabrication and measurement of physical models. It is also worth noting that in today's world, the advantages of using CEM tools translate into the reduced carbon footprint of research and development of electromagnetic devices, structures, and systems.

As a community, we have recently celebrated 150 years of Maxwell's equations, and CEM has a history of more than 50 years. There has been tremendous progress that CEM researchers have made in developing new methods and codes, both "in-house" (research or custom-designed) techniques and commercial solvers, often in synergy with users of these methods in various application and research areas. This special issue of the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION (TAP) showcases the most recent developments, ideas, and results constituting the state-of-the-art in CEM techniques to simulate the problems of antennas and propagation and discusses the best and visionary approaches as we move forward. Namely, we are not yet done in solving these four 150-year-old equations, as we continue to strive for faster, more accurate, versatile, and reliable CEM simulations, for different classes of real-world engineering applications and problems.

This special issue on CEM follows suit of the two previous TAP special issues, namely, the 2008 Special Issue, entitled Large and Multiscale Computational Electromagnetics, and the one published in 1997, on Advanced Numerical Techniques in Electromagnetics. These issues not only provided comprehensive accounts of the state-of-the-art in the field and archival materials that have been heavily cited and used but also set stage for subsequent research, development, and practice in CEM for long periods of time. We hope that the TAP Special Issue on Frontiers in Computational Electromagnetics will be equally useful and impactful in shaping the future of CEM and its applications.

The special issue features frontiers in CEM at the intersection of methods, computing, and applications. Its papers demonstrate advances in all major CEM methodologies

Digital Object Identifier 10.1109/TAP.2023.3337967

and numerical discretization techniques, including integral-equation, finite-element/difference, asymptotic, and hybrid CEM modeling, in both frequency and time domains. Some works show advancements in accuracy, efficiency, reliability, and robustness of CEM simulations or address error estimation, adaptive refinement, automation, and optimization in CEM, while others are devoted to exploiting advantages of emerging and growing computing hardware and software infrastructure for CEM. Because of the production deadlines, the special issue is split into two parts.

There are 17 papers in Part I. It starts with nine papers on time-domain solvers and methods and then proceeds with five on surface integral equation (SIE) solvers and three on discretization and refinement techniques.

A. *Time-Domain Solvers*

The first group of time-domain solvers is the state-of-the-art finite-different time-domain (FDTD) methods. Cheng et al. [A1] improve the stability of the classical FDTD method using the so-called summation by parts simultaneous approximation term (SBP-SAT) technique and demonstrate the applicability of SBP-SAT-FDTD by a set of numerical experiments involving real-life engineering problems. Wang et al. [A2] carry out a comprehensive numerical dispersion analysis and provide a stability condition for a nonuniform FDTD scheme used for solving Maxwell equations on the face-centered cubic (FCC) grid. Their results show the improved accuracy of classical FDTD methods. Dang et al. [A3] describe a symmetric subgridding technique, which ensures the long-time stability of the FDTD scheme when it is applied to multiscale structures. They provide a rigorous stability analysis of this enhanced FDTD scheme and apply the scheme to simulation of resonators to numerically demonstrate long-time stability. Wang and Ren [A4] hybridize an FDTD scheme for Maxwell equations and a finite-element time-domain (FETD) scheme for wave equations. Carefully stitching these solvers together while using an implicit time integrator for FETD and an explicit one for FDTD yields a framework that is more efficient than traditional hybrid FETD/FDTD methods.

The second group of time-domain solvers focuses on discontinuous Galerkin time-domain (DGTD) schemes. Li et al. [A5] present a new p-adaptive refinement technique combined with a local time stepping strategy. This technique uses a local maximal error in each discretization element to determine the allowable local range for p and a simple grouping approach to rapidly perform the marching-on-in-time procedure. Zhou et al. [A6] propose a DGTD scheme that relies on second-order bilinear z transform (BZT) to analyze the behavior of electromagnetic waves in a magnetized cold plasma. Their analysis and results show that the BZT-DGTD scheme is more stable and faster and avoids aliasing effects more effectively than existing methods. Cao and Ren [A7] first formulate a new upwind flux to consider the bi-isotropy in the material properties and then develop a DGTD scheme that relies on this new numerical flux to simulate transient electromagnetic field interactions on arbitrarily shaped 3-D bi-isotropic objects.

The third group of papers focuses on time-domain integral equations. Sayed et al. [A8] propose a time-domain electric field volume integral equation solver to analyze electromagnetic field interactions on dielectric objects with Kerr nonlinearity. This new method uses an explicit marching-on-in-time scheme to eliminate the need for computationally costly Newton-like nonlinear solvers and outperforms the traditional FDTD method in accuracy. Aktepe and Ülkü [A9] present a novel semianalytical scheme to evaluate the retarded-time potentials due to impulsively excited Rao–Wilton–Glisson (RWG) functions defined on curvilinear triangles. This scheme eliminates the need for singularity treatment and can achieve accuracy at the machine precision level using a suitable order Gauss–Legendre integration rule.

B. *SIE Solvers*

In Part I of this special issue, there are five papers focusing on SIE solvers. Hofmann et al. [A10] propose a novel discretization method for the right-hand side of a quasi-Helmholtz preconditioned electric field integral equation on multiply-connected geometries. Their method is excitation agnostic and low-frequency stable, enabling accurate computations of scattered and radiated fields under arbitrary excitations. Merlini et al. [A11] introduce the concept of filtered quasi-Helmholtz decompositions, which can be used to derive new families of preconditioners and fast solvers. They present the first application of these decompositions to the frequency and h-refinement preconditioning of the electric field integral equation and demonstrate their effectiveness by several numerical results. Martin et al. [A12] describe a multiresolution preconditioner to improve the iterative convergence of the SIE solvers that are used with nonconformal meshes. The multibranch RWG basis functions are used to discretize the unknown currents and an automatic multilevel quasi-Helmholtz decomposition algorithm is developed for preconditioning. A parallelized version of the preconditioner is used in the simulation of electrically large multiscale objects discretized using an h-refinement strategy. Zvulun et al. [A13] present a novel integral equation formulation for scattering from impenetrable and convex bodies using generalized directional sources, which enhance low-rank approximation-based matrix compression and facilitate the development of fast direct solvers. Directional sources call for computation of a modified Green function, which is done efficiently using nonuniform sampling and tabulation. Peterson [A14] evaluates the performance of four residual error estimators for perfectly conducting targets in the context of the SIE solvers using RWG functions for discretization. His results show that tangential-field residuals are more reliable than normal-field residuals for assessing accuracy and residuals are sensitive to internal resonance modes and can be used to detect spurious solutions.

C. *Discretization and Refinement Techniques*

Finally, there are three papers focusing on new discretization and refinement techniques in Part I of this special issue. Graglia [A15] describes a new method for constructing hierarchical vector bases for the pyramid discretization elements.

This method utilizes a new technique that maps a pyramid into a cube of a new Cartesian space, enabling the construction of face-based functions of zero polynomial order and volume-based functions of the first order. Functions of arbitrarily high order are obtained by multiplying the vector functions of the lowest order by independent scalar polynomials of higher order. Tobon et al. [A16] present a novel domain decomposition method for the electromagnetic analysis of multiscale structures using SIEs. The method utilizes the Huygens equivalence principle to decompose the structure into domains, enabling efficient *h*-refinement and local error estimation. The adaptive *h*-refinement procedure, coupled with nonconformal submeshing and multibranch RWG basis functions, effectively addresses the complexity of structures with varying scales. Harmon et al. [A17] introduce refinement-by-superposition (RBS) to the CEM community and propose a new multilevel *hp*-refinement technique that achieves exponential rates of convergence, drastically reduces the implementation complexity, and does not suffer from practical limitations of constrained-node refinement. Numerical simulations for the 2-D FE solution of the Maxwell eigenvalue problem demonstrate the effectiveness of RBS.

These papers, along with those appearing in Part II of this special issue, clearly demonstrate that the state of CEM for antennas and propagation, as well as other applications, is indeed very strong. While this special issue highlights significant advancements in the field, many challenges and open problems remain in CEM-based analysis, modeling, and design. We anticipate the emergence of numerous groundbreaking CEM approaches in computational methodologies, numerical discretization techniques, and harnessing the ever-increasing computing power, all fueled by future applications and evolving challenges. So, until the next TAP CEM special issue. Are those four, now more than 150 years old, Maxwell's equations ever going to be definitely solved?

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APPENDIX: RELATED ARTICLES

[A1] Y. Cheng et al., "Towards the development of a three-dimensional SBP-SAT FDTD method: Theory and validation," *IEEE Trans. Antennas Propag.*, vol. 71, no. 12, pp. 9178–9193, Dec. 2023.

[A2] X. Wang, G. Chen, S. Yang, Y. Li, W. Du, and D. Su, "An FCC-FDTD method on nonuniform grids with guaranteed stability for electromagnetic analysis," *IEEE Trans. Antennas Propag.*, vol. 71, no. 12, pp. 9194–9206, Dec. 2023.

[A3] L. Deng et al., "A symmetric FDTD subgridding method with guaranteed stability and arbitrary grid ratio," *IEEE Trans. Antennas Propag.*, vol. 71, no. 12, pp. 9207–9221, Dec. 2023.

[A4] J. Wang and Q. Ren, "A 3-D hybrid Maxwell's equations finite-difference time-domain (ME-FDTD)/wave equation finite-element time-domain (WE-FETD) method," *IEEE Trans. Antennas Propag.*, vol. 71, no. 6, pp. 5212–5220, Jun. 2023.

[A5] S. P. Li, Y. Shi, S. C. Zhu, and Z. G. Ban, "A global–local error-driven *p*-adaptive scheme for discontinuous Galerkin time domain method with local time stepping strategy," *IEEE Trans. Antennas Propag.*, vol. 71, no. 12, pp. 9222–9232, Dec. 2023.

[A6] Y. Zhou, L. Wang, Q. Ren, B. Liang, and Q. H. Liu, "Simulation of electromagnetic waves in magnetized cold plasma by a novel BZT-DGTD method," *IEEE Trans. Antennas Propag.*, vol. 71, no. 12, pp. 9233–9244, Dec. 2023.

[A7] H. Cao and Q. Ren, "Novel discontinuous Galerkin time-domain method for analyzing scattering from three-dimensional bi-isotropic objects," *IEEE Trans. Antennas Propag.*, vol. 71, no. 12, pp. 9245–9254, Dec. 2023.

[A8] S. B. Sayed, R. Chen, H. A. Ulku, and H. Bagci, "A time domain volume integral equation solver to analyze electromagnetic scattering from nonlinear dielectric objects," *IEEE Trans. Antennas Propag.*, vol. 71, no. 12, pp. 9255–9267, Dec. 2023.

[A9] A. Aktepe and H. A. Ülkü, "Evaluation of the retarded-time potentials due to an impulsively excited curvilinear RWG function," *IEEE Trans. Antennas Propag.*, vol. 71, no. 12, pp. 9268–9276, Dec. 2023.

[A10] B. Hofmann, T. F. Eibert, F. P. Andriulli, and S. B. Adrian, "A low-frequency stable, excitation agnostic discretization of the right-hand side for the electric field integral equation on multiply-connected geometries," *IEEE Trans. Antennas Propag.*, vol. 71, no. 12, pp. 9277–9288, Dec. 2023.

[A11] A. Merlini, C. Henry, D. Consoli, L. Rahmouni, A. Dély, and F. P. Andriulli, "Laplacian filtered loop-star decompositions and quasi-Helmholtz filters: Definitions, analysis, and efficient algorithms," *IEEE Trans. Antennas Propag.*, vol. 71, no. 12, pp. 9289–9302, Dec. 2023.

[A12] V. F. Martin, J. M. Taboada, and F. Vipiana, "A multi-resolution preconditioner for non-conformal meshes in the MoM solution of large multi-scale structures," *IEEE Trans. Antennas Propag.*, vol. 71, no. 12, pp. 9303–9315, Dec. 2023.

[A13] D. Zvulun, Y. Brick, and A. Boag, "A generalized source integral equation for enhanced compression in three dimensions," *IEEE Trans. Antennas Propag.*, vol. 71, no. 12, pp. 9316–9325, Dec. 2023.

[A14] A. F. Peterson, "Integral equation residuals for error estimation and internal resonance detection," *IEEE Trans. Antennas Propag.*, vol. 71, no. 12, pp. 9326–9333, Dec. 2023.

[A15] R. D. Graglia, "Hierarchical divergence-conforming vector bases for pyramid cells," *IEEE Trans. Antennas Propag.*, vol. 71, no. 12, pp. 9334–9343, Dec. 2023.

[A16] J. Tobon, V. F. Martin, A. Serna, Z. Peng, and F. Vipiana, "On the use of a localized Huygens' surface scheme for the adaptive H-refinement of multi-scale problems," *IEEE Trans. Antennas Propag.*, vol. 71, no. 12, pp. 9344–9356, Dec. 2023.

[A17] J. J. Harmon, J. Corrado, and B. M. Notaroš, "A refinement-by-superposition *hp*-method for $H(\mathrm{curl})$- and $H(\mathrm{div})$-conforming discretizations," *IEEE Trans. Antennas Propag.*, vol. 71, no. 12, pp. 9357–9364, Dec. 2023.