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Versatile and accurate schemes of discretization for the electromagnetic scattering analysis of arbitrarily shaped piecewise homogeneous objects

Ivan Sekulic *, Eduard Ubeda, Juan M. Rius

CommSensLab, Universitat Politecnica de Catalunya (BarcelonaTech), Jordi Girona 1-3, 08034 Barcelona, Spain

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ABSTRACT

The discretization by the method of moments (MoM) of integral equations in the electromagnetic scattering analysis most often relies on divergence-conforming basis functions, such as the Rao–Wilton–Glisson (RWG) set, which preserve the normal continuity of the expanded currents across the edges arising from the discretization of the target boundary. Although for such schemes the boundary integrals become free from hyper-singular kernel-contributions, which is numerically advantageous, their practical implementation in real-life scenarios becomes particularly cumbersome. Indeed, the application of the normal continuity condition on composite objects becomes elaborate and convoluted at junction-edges, where several regions intersect. Also, such edge-based schemes cannot even be applied to nonconformal meshes, where adjacent facets may not share single matching edges. In this paper, we present nonconforming schemes of discretization for the scattering analysis of complex objects based on the expansion of the boundary unknowns, electric or magnetic currents, with the facet-based monopolar-RWG set. We show with examples how these schemes exhibit great flexibility when handling composite piecewise homogeneous objects with junctions or targets modeled with nonconformal meshes. Furthermore, these schemes offer improved near- and far-field accuracy in the scattering analysis of electrically small single sharp-edged dielectric targets with moderate or high dielectric contrasts.

1. Introduction

The accurate scattering analysis of complex targets, made up of homogeneous components with different electromagnetic properties, is of great interest nowadays for the engineering community. The surface integral equations, such as the electric-field integral equation (EFIE) [1] and the Poggio–Miller–Chang–Harrington–Wu–Tsai (PMCHWT) [2–4] formulation, arise from setting currents and field boundary conditions over the surface interfaces between different regions. These schemes, which satisfy by definition the radiation condition at infinity, are normally preferred in the scattering analysis of homogeneous targets, perfectly conducting (PEC) or penetrable, over other numerical schemes, such as the volume integral equations [5], which require the definition of unknowns inside regions, or the finite-element methods [6,7] which call for the explicit insertion of absorbing boundary conditions [8]. In the Galerkin discretization by the method of moments

* Corresponding author.
E-mail addresses: ivan.sekulic@tsc.upc.edu (I. Sekulic), ubeda@tsc.upc.edu (E. Ubeda), rius@tsc.upc.edu (J.M. Rius).

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[9] of surface-integral equations, the currents and the tangential traces of the field spaces over the boundary interfaces are expanded and tested, respectively, with the same set of basis functions. Typically, these are divergence-conforming sets, such as the RWG set, which enforce normal continuity across the edges arising from the discretization and span a finite-dimensional subspace inside $\mathcal{H}^{-1/2}(\mathrm{div}_{\partial\Omega}, \partial\Omega)$ [10], the function space that encompasses the space of currents and the dual of the range of the tangential-trace operators [11–13]. Galerkin-discretizations with the RWG basis functions of the EFIE and PMCHWT formulations [1,14] excel as conforming schemes, hence with converging solutions in the physical space of currents [15,16]. Moreover, these implementations are numerically advantageous because the hypersingular kernel contributions cancel out.

The well-established conforming scattering analysis for single homogeneous objects can be extended straightforwardly to composite objects without junctions, such as coated metallic objects or multilayered penetrable structures [17,18]. However, the development of conforming schemes for composite objects with junctions, viz. boundary lines where more than two regions intersect, becomes somewhat awkward because of the definition of special continuity conditions at junctions [19–23]. In any case, these *single-surface* (or *single-trace*) approaches have been successful for decades in the analysis of composite structures despite the involved search of junctions and the required identification of the number and type (metallic or penetrable) of intersecting regions at each junction. More recently, other so-called *two-surface* [24] or *multi-trace* [25] schemes circumvent the management of junctions by treating the composite object as a set of disjoint objects immersed in a host medium, with the separation distances tending to zero. These schemes provide improved flexibility when managing composite objects but require the definition of additional redundant unknowns at touching surfaces. Clearly, the single-trace approaches were developed in earlier times, with restricted computational resources, such that the definition of additional unknowns was just too costly. Conversely, over the past years, the double-surface and multi-trace schemes have captured the attention of researchers thanks to the dramatic increase of available memory resources.

All these schemes suffer from the mesh restrictions imposed by the adopted divergence-conforming sets, which need to be defined over conformal meshes, with all pairs of adjacent facets sharing a single edge. In consequence, the mesh generation of composite objects in the single-trace analysis becomes especially constrained, inadequate to combine arbitrary meshes arising from the independent tessellation of each of the several subdomains that form the original structure. Similarly, although the double-surface and multi-trace techniques allow the juxtaposition of closed meshes linked to each subdomain, the meshing schemes adopted must be in any case locally conformal over each subdomain. Hence, the application of such schemes to nonconformal meshes, where adjacent facets may not share single edges, appears unworkable. This has some impact in the analysis of real-life complex structures, especially when the mesh under analysis arises from the interconnection of open arbitrary triangulations.

In this work, we address the robust, accurate and versatile single-surface scattering analysis of dielectric objects with arbitrary shape and composite objects with junctions. For this, we employ the EFIE–PMCHWT integral-equation formulation [21], which follows from the application of the EFIE or PMCHWT formulations over boundary surfaces, respectively, enclosing PEC regions or separating penetrable regions. The proposed schemes rely on the expansion of the currents with the facet-based, discontinuous-across-edges, monopolar-RWG set [26–29]. This choice gives rise to boundary integrals with hypersingular kernels, which we handle by testing the equations with well-suited testing functions defined off the boundary tessellation, inside the region where, in light of the surface equivalence principle, the fields must be zero. The *volumetric* scheme of testing defines the testing functions over small volumetric domains, tetrahedral elements or wedges, attached to the boundary surface [27,28]. The *tangential-normal* scheme deploys RWG testing functions over pairs of adjacent triangles such that one triangle matches a boundary triangle and the other one is quasi-normally oriented into the null-field region [29]. These implementations are nonconforming since the finite-dimensional spaces spanned by the monopolar-RWG functions belong to the space of square-integrable functions $L^2(\partial\Omega)$ [30]. Interestingly, they exhibit similar or better accuracy than the conventional RWG-schemes in the scattering analysis of targets with sharp edges and corners, PEC [27–29,31] or 2D TE-dielectric [32], especially if moderately small. Note that for a given discretization the monopolar-RWG space includes the space spanned by the RWG basis functions [27].

As we show in the paper, our nonconforming PMCHWT implementations exhibit improved accuracy when compared with the RWG-schemes in the analysis of single small sharp-edged dielectric objects with moderate or high dielectric contrasts. Moreover, our schemes manifest in general great flexibility in the single-surface analysis of composite objects with junctions as the special modeling of currents at junctions is not required. Also, the proposed implementations can handle nonconformal meshes when applied to piecewise (or fully) homogeneous arbitrarily shaped objects. This represents significant progress with respect to previous schemes, mainly addressing nonconformal meshes of homogeneous 3D targets, PEC [27–30] or dielectric [33,34], or 2D composite objects [32]. Our schemes become also well suited for the enhancement of integral-equation domain decomposition methods [34–36], since the transmission conditions between contiguous subdomains may be satisfied through the off-boundary testing and the discontinuous monopolar-RWG expansion.

In Section 2, details on the monopolar-RWG discretization of the PMCHWT formulation, with off-boundary testing, are provided. Special emphasis is given on the wedge volumetric and the tangential-normal schemes of testing, while details on the tetrahedral testing are already available in [37]. In Section 3, the analysis of piecewise homogeneous composite objects with the monopolar-RWG discretization of the single-surface EFIE–PMCHWT formulation is described. The difficulties in the management of junctions with the conventional schemes are described together with the advantages of our nonconforming discretizations. In Section 4, results for the various monopolar-RWG schemes of discretization of the EFIE–PMCHWT formulation, with volumetric or tangential-normal testing, are shown and discussed.