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Abstract

This paper addresses novel techniques and algorithms for automated electromagnetic (EM) optimization suitable for design of RF, wireless and microwave circuits and structures. We discuss the utilization of "Datapipes" in optimizing microwave circuits. Advanced interpolation and database techniques are integrated to reduce the number of EM field analyses. The Geometry Capture technique for parameterizing arbitrary geometrical structures is described. We review the exciting Space Mapping concept. We discuss the newly proposed trust region aggressive space mapping technique.

DATAPIPE ARCHITECTURE

OSA introduced the Datapipe concept to make full use of the power of disjoint simulators. This architecture enables the optimizer to drive a simulator through an optimization driver. It has been implemented in the commercial software system OSA90/hope [1].

Datapipes are flexibly defined in the input file. The user specifies a set of inputs from OSA90 to the external program and defines outputs to be returned. The external programs are run in separate processes and communicate with OSA90 in a manner similar to subroutine calls.

The first Datapipe driver developed by OSA was the Empipe interface to Sonnet's ***em*** [2]. ***em*** is an efficient full-wave MoM field solver for predominantly planar circuits. In addition to Empipe, a number of specialized Datapipe-based interfaces have been developed for a number of applications, including the popular analog circuit simulator SPICE and the FEM field solvers Maxwell Eminence [3] and HFSS [4].

With the acquisition of OSA by HP EEsof in 1997 this technology is being merged with future HP EEsof products.

INTERPOLATION AND DATABASE TECHNIQUES

Interpolation and database techniques are integrated within the optimization driver to reduce the number of EM field analyses required as well as to facilitate gradient calculations. Interpolation may be necessitated by an EM simulator if the particular solver used employs a fixed grid meshing scheme, for example ***em***. If not enforced by the solver, interpolation is still a highly desirable feature.

If interpolation is employed, EM simulations are performed at on-grid points only. For off-grid points, user-selectable linear or quadratic interpolation schemes have been adopted. Also selectable by the user are the parameters to be interpolated: S, Y or Z, in either rectangular or polar form. For example, in the case of linear interpolation we have [5]

$$R(\phi) = R_{em}(\phi^c) + \theta^T \, \text{sign}\,\Theta \, \Delta \boldsymbol{R}_{em}(\boldsymbol{B}) \qquad (1)$$

where

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$$\Delta\boldsymbol{R}_{em}(\boldsymbol{B}) = [\ R_{em}(\phi^{1})\text{-}R_{em}(\phi^{c}) \quad R_{em}(\phi^{2})\text{-}R_{em}(\phi^{c}) \quad R_{em}(\phi^{n})\text{-}R_{em}(\phi^{c})]^{T} \qquad (2)$$

$\boldsymbol{B}$ is the set of base points used for interpolation, R_{em} denotes the response being interpolated, ϕ^c is the center (on-grid) base point, and ϕ^1, ϕ^2, ..., ϕ^n are n (also on-grid) base points obtained by perturbing each parameter ϕ_i by its (plus or minus) discretization step d_i, one at a time. θ and Θ represent the relative (w.r.t. the discretization step) deviation of the off-grid point ϕ from ϕ^c, arranged in a vector or a diagonal matrix form, respectively. The gradient of (1), which is the function actually seen by the optimizer, is also readily available as

$$\frac{\partial R(\phi)}{\partial \phi} = \boldsymbol{D}^{-1}\ \text{sign}\Theta\ \Delta\boldsymbol{R}_{em}(\boldsymbol{B}) \qquad (3)$$

where $\boldsymbol{D} = \text{diag}\{d_i\}$.

The results of on-grid simulations are stored in a database system for efficient re-use during subsequent interpolations at other off-grid points for which some or all of the base points may have already been simulated.

GEOMETRY CAPTURE

This section addresses the critical issue [6] of parameterization of geometrical structures for the purpose of layout-based design, in particular automated EM optimization. As the optimization process proceeds, revised structures must be automatically generated. Moreover, each such structure must be physically meaningful and should follow the designer's intention w.r.t. allowable modifications and possible limits. It is of utmost importance to leave the parameterization process to the user. In an earlier work [7], we created a library of predefined elements (lines, junctions, bends, gaps, etc.), that were already parameterized and ready for optimization. The applicability of that approach is, however, limited to structures that are decomposable into the available library elements. Moreover, even a comprehensive library would not satisfy all microwave designers, simply because of their creativity in devising new structures. Furthermore, the library approach inherently omits possible proximity couplings between the elements since they are individually simulated by an EM solver and connected by a circuit-level simulator.

Geometry Capture facilitates user parameterization of arbitrary structures by processing the native files of the respective EM simulators. A new approach was implemented in the optimization drivers Empipe and Empipe3D [1]. For example, in Empipe designable parameters and optimization variables are automatically captured from a set of "geo" files created using ***xgeom***. Similarly, in Empipe3D the optimization variables are captured from a set of Maxwell Eminence or HFSS projects. These projects, or "geo" files reflect the structure evolution in response to parameter changes. The user's graphical inputs are processed to define optimizable variables. Once a structure is captured, the modified project files are automatically generated, and then the field solver is invoked to display and optimize, for instance, the S-parameter responses. The captured structures are as easy to use as conventional circuit elements. In addition to geometrical dimensions, dielectric and other material parameters can also be selected for optimization.

SPACE MAPPING OPTIMIZATION

We consider models in two distinct spaces, namely the optimization space denoted by $\boldsymbol{X}_{os}$, and the EM space denoted by $\boldsymbol{X}_{em}$. We assume that the $\boldsymbol{X}_{os}$ model is much faster to evaluate but less accurate than the $\boldsymbol{X}_{em}$ model. The $\boldsymbol{X}_{os}$ model can be an empirical model or a coarse-resolution EM model. We wish to find a mapping $\boldsymbol{P}$ between these two spaces, i.e., a function that maps the parameters of one model onto the parameters of the other model [8]:

$$\boldsymbol{x}_{os} = \boldsymbol{P}(\boldsymbol{x}_{em}) \qquad (4)$$

such that

$$\boldsymbol{R}_{os}(\boldsymbol{P}(\boldsymbol{x}_{em})) \approx \boldsymbol{R}_{em}(\boldsymbol{x}_{em}) \qquad (5)$$

where $\boldsymbol{R}_{os}(\boldsymbol{x}_{os})$ and $\boldsymbol{R}_{em}(\boldsymbol{x}_{em})$ denote the model responses in the respective spaces.

The purpose of Space Mapping (SM) is to avoid direct optimization in the computationally expensive $\boldsymbol{X}_{em}$ space. We perform optimization in $\boldsymbol{X}_{os}$ to obtain the optimal design $\boldsymbol{x}_{os}^*$ and then use SM to find the mapped solution in $\boldsymbol{X}_{em}$ as

$$\bar{\boldsymbol{x}}_{em} = \boldsymbol{P}^{-1}(\boldsymbol{x}_{os}^{*}) \qquad (6)$$

$\boldsymbol{P}$ is found by an iterative process starting from $\boldsymbol{x}_{em}^{(1)}$ 1 = $\boldsymbol{x}_{os}^{*}$. At the *i*th step, the $\boldsymbol{X}_{em}$ model is simulated at $\boldsymbol{x}_{em}^{(i)}$, i.e., the current parameter values. If the $\boldsymbol{X}_{em}$ model does not produce the desired responses we perform parameter extraction of the $\boldsymbol{X}_{os}$ model to find $\boldsymbol{x}_{os}^{(i)}$ which minimizes

$$\|\boldsymbol{R}_{os}(\boldsymbol{x}_{os}^{(i)}) - \boldsymbol{R}_{em}(\boldsymbol{x}_{em}^{(i)})\| \qquad (7)$$

where $\|\ \|$ denotes a suitable norm. In the aggressive SM (ASM) strategy [9] the next iterate is found by a quasi-Newton step

$$\boldsymbol{x}_{em}^{(i+1)} = \boldsymbol{x}_{em}^{(i)} + (\boldsymbol{B}^{(i)})^{-1}(\boldsymbol{x}_{os}^{*} - \boldsymbol{x}_{os}^{(i)}) \qquad (8)$$

which employs an approximate Jacobian matrix $\boldsymbol{B}^{(i)}$. The matrix $\boldsymbol{B}^{(i)}$ is subsequently updated using the Broyden formula [10].

The parameter extraction step utilized in the ASM technique for evaluating $\boldsymbol{P}(\boldsymbol{x}_{em}^{(i)})$ may be nonunique. This may hinder the convergence of the algorithm. The Trust Region ASM algorithm (TRASM) [11] was developed to overcome this difficulty. The technique integrates a trust region methodology with the ASM technique. The step taken at the *i*th iteration is given by

$$(\boldsymbol{B}^{(i)T}\boldsymbol{B}^{(i)} + \lambda \boldsymbol{I})\boldsymbol{h}^{(i)} = -\boldsymbol{B}^{(i)T}\boldsymbol{f}^{(i)} \qquad (9)$$

subject to $\|\boldsymbol{h}^{(i)}\| \leq \delta$, where δ is the size of the trust region. The value of the parameter λ is correlated with the value of δ and is evaluated using the method described in [12].

The algorithm also utilizes a recursive multi-point parameter extraction step. Each time the new point suggested in (9) fails to satisfy a certain success criterion a temporary point is added to the set of points used for multi-point parameter extraction. The parameter extraction step is given by

$$\underset{\boldsymbol{x}_{os}}{\mathit{minimize}} \left\| \boldsymbol{R}_{os}(\boldsymbol{x}_{os} + \boldsymbol{B}^{(i)}(\boldsymbol{x}_{em} - \boldsymbol{x}_{em}^{(i+1)})) - \boldsymbol{R}_{em}(\boldsymbol{x}_{em}) \right\| \qquad (10)$$

for a set of points $\boldsymbol{x}_{em}$. It is clear from (10) that the current mapping between the two models which is given by the matrix $\boldsymbol{B}^{(i)}$ is exploited in the multi-point parameter extraction.

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