Fast Antenna Optimization Using Gradient Monitoring and Variable-Fidelity EM Models

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***Abstract*—Accelerated simulation-driven design optimization of antenna structures is proposed. Variable-fidelity electromagnetic (EM) analysis is used as well as the trust-region framework with limited sensitivity updates. The latter are controlled by monitoring the changes of the antenna response gradients. Our methodology is verified using three compact wideband antennas. Comprehensive benchmarking demonstrates its superiority over both conventional and surrogate-assisted algorithms.**

Keywords—antenna optimization, EM-driven design, trust-region framework, variable-fidelity EM simulations.

I. INTRODUCTION

Adjustment of geometry parameters is a necessary yet challenging stage of the antenna design process. Due to the complexity of contemporary structures, numerical optimization is recommended, and more and more widely used by the researchers [1]. Its major bottleneck, which is high CPU cost, can be alleviated by various means, e.g., utilization of adjoints sensitivities [2], surrogate modeling techniques [3], or by developing more efficient numerical routines [4]. This paper proposes a modification of the trust-region gradient search procedure aimed at improving the computational efficiency. Its two major components include variable-fidelity EM simulations (to speed up sensitivity estimation), as well as antenna response gradient monitoring (to reduce the number of expensive finite-differentiation-based sensitivity updates). Both mechanisms lead to a considerable reduction of the overall cost of the optimization process as demonstrated through examples. Furthermore, the proposed technique is shown competitive to both traditional and multi-fidelity algorithms.

II. VARIABLE-FIDELITY GRADIENT SEARCH WITH SPARSE SENSITIVITY UPDATES

For illustration purposes, the task of antenna matching improvement is considered, which can be formulated as:

$$\boldsymbol{x}^* = \arg\min\{\boldsymbol{x} : U(\boldsymbol{x})\}. \tag{1}$$

Here, $\boldsymbol{x}$ is a vector of antenna parameters, whereas the objective function is defined as $U(\boldsymbol{x}) = \max\{f \in F : |S_{11}(\boldsymbol{x},f)|\}$, where f is the frequency within the range of interest F (e.g., 3.1 GHz to 10.6 GHz for UWB antennas). The reflection characteristic $S_{11}(\boldsymbol{x},f)$ is obtained through a high-fidelity EM analysis.

The core of the proposed framework is the conventional trust-region (TR) gradient-based algorithm [5] solving (1) by producing approximations $\boldsymbol{x}^{(i)}$, $i = 0, 1, \ldots$, to $\boldsymbol{x}^*$ as:

$$\boldsymbol{x}^{(i+1)} = \arg\min_{\boldsymbol{x};\,-\boldsymbol{d}^{(i)} \le \boldsymbol{x}-\boldsymbol{x}^{(i)} \le \boldsymbol{d}^{(i)}} U_S(\boldsymbol{x}), \tag{2}$$

where $U_S(\boldsymbol{x}) = \max\{f \in F : S_L^{(i)}(\boldsymbol{x},f)\}$, and $S_L^{(i)}$ is defined as:

$$S_L^{(i)}(\boldsymbol{x}, f) = S_{11}(\boldsymbol{x}^{(i)}, f) + \boldsymbol{G}_S(\boldsymbol{x}^{(i)}) \cdot (\boldsymbol{x} - \boldsymbol{x}^{(i)}). \tag{3}$$

In (2), $\boldsymbol{d}^{(i)}$ is the TR size at the ith iteration, adjusted using the standard rules [5]. The gradient $\boldsymbol{G}_S$ is normally evaluated using finite differentiation (FD), which is the major contributor to the CPU cost of the process.

Here, we employ two mechanisms to reduce the cost of solving (1). The first one is utilization of a coarse-mesh EM antenna model $S_{11.c}(\boldsymbol{x},f)$ for the purpose of sensitivity estimation. As indicated in Fig. 1, despite noticeable discrepancies between the high- and low-fidelity models, the gradients are well aligned which makes the use of $S_{11.c}$ a reasonable (and, of course, cheaper) option.

The second technique is monitoring of the antenna response gradients aimed at detecting their stable patterns and, consequently, suppressing unnecessary FD updates. Here, we deal with the antenna reflection $S_{11}(\boldsymbol{x},f)$, for which the gradient $\boldsymbol{G}_S = [G_1 \ \ldots \ G_n]$ is a $1 \times n$ vector. The components G_k are compared between the algorithm iterations using a metric:

$$d_k^{(i+1)} = \underset{f \in F}{mean}\left(2\left[\left|G_k^{(i)}(f)\right| - \left|G_k^{(i-1)}(f)\right|\right] \Big/ \left[\left|G_k^{(i)}(f)\right| + \left|G_k^{(i-1)}(f)\right|\right]\right), \tag{4}$$

where $G_k^{(i)}(f)$ and $G_k^{(i-1)}(f)$ refer to the ith and (i–1)th iteration, respectively. The averaging is over the frequency range F. We also define a vector $\boldsymbol{d}^{(i)} = [d_1^{(i)} \ \ldots \ d_n^{(i)}]^T$ of the gradient difference factors used in the i-th iteration, $d_{\min}^{(i)} = \min\{k = 1,\ldots,n : d_k^{(i)}\}$, and $d_{\max}^{(i)} = \max\{k = 1,\ldots,n : d_k^{(i)}\}$. Furthermore, in the i-th iteration, a vector $\boldsymbol{N}^{(i)} = [N_1^{(i)} \ \ldots \ N_n^{(i)}]^T$ will stand for the numbers of subsequent iterations without FD. Its components are computed according to the conversion function:

$$N_k^{(i)} = \left[\!\left[N_{\max} + a^{(i)}(d_k^{(i)} - d_{\min}^{(i)}) \right]\!\right], \tag{5}$$

where $a^{(i)} = (N_{\max} - N_{\min})/(d_{\min}^{(i)} - d_{\max}^{(i)})$ and [[.]] is the nearest integer function. The function (5) establishes a relation between $N_k^{(i)}$ and $d_k^{(i)}$, which is based on the minimum and the maximum number of iterations without FD (algorithm control parameters). Given $N_k^{(i)}$, $N_k^{(i+1)}$ is obtained from (%) if FD was executed for the kth parameter in the ith iteration, otherwise $N_k^{(i+1)} = N_k^{(i)} - 1$. The maximum number of omissions is $N_{\max}$. The values of the difference factors $d_k^{(i)}$ retained through all the iterations without FD. They are utilized to determine $d_{\min}^{(i)}$ and $d_{\max}^{(i)}$ as well as to compute $N_k^{(i)}$ for other parameters.

In the proposed optimization framework, the gradient $\boldsymbol{G}_S$ is estimated using FD only in the first two iterations. Further, the

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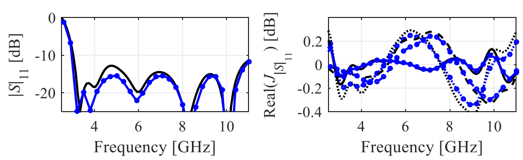
gradient is exclusively computed using the low-fidelity EM model. In the remaining iterations, the components G_k are obtained based on $\boldsymbol{N}^{(i+1)}$: if $N_k^{(i)} = 1$, FD is performed, otherwise the most recent value estimated with FD is kept. This allows for a significant reduction of the computational cost of the optimization process.

III. Verification Examples

The test set consists of three antennas shown in Fig. 2. Antenna I, [6] is implemented on Taconic RF-35 substrate (ε_r = 3.5, h = 0.762 mm). It is described by parameters $\boldsymbol{x} = [l_0\ g\ a\ l_1\ l_2\ w_1\ o]^T$; $w_0 = 2o + a$, and w_f = 1.7 mm. Antenna II [7] is also implemented on RF-35; geometry parameters are $\boldsymbol{x} = [L_0\ dR\ R\ r_{rel}\ dL\ dw\ L_g\ L_1\ R_1\ dr\ c_{rel}]^T$. Antenna III [8] is implemented on FR4 (ε_r = 4.3, h = 1.55 mm); design parameters are $\boldsymbol{x} = [L_g\ L_0\ L_s\ W_s\ d\ dL\ d_s\ dW_s\ dW\ a\ b]^T$. All antennas are to operate within the UWB frequency range of 3.1 GHz to 10.6 GHz. The EM models are implemented in CST. The models incorporate the SMA connectors.

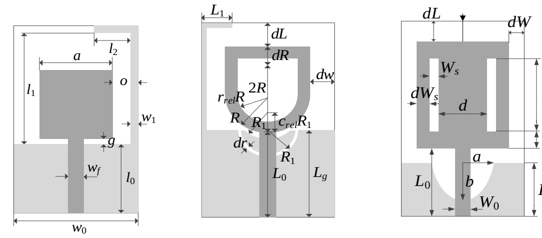
The antennas have been optimized for best matching, using the proposed algorithm with $N_{\min} = 1$ and $N_{\max} = 5$. Three other algorithms were also tested for comparison: (i) the TR algorithm (2), (3) working with the high-fidelity model only, (ii) the reference algorithm working with variable-fidelity models, and (iii) the algorithm of Section II working with the high-fidelity model only. To test the robustness, ten runs have been executed for each algorithm using random initial designs. Table I gathers the numerical data (see also Fig. 3).



(a) (b)

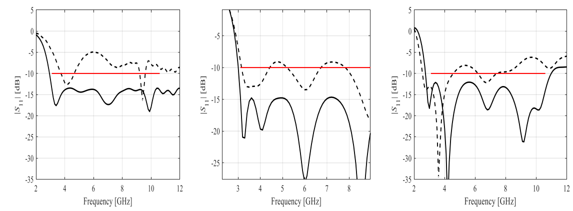
Fig. 1. Example $|S_{11}|$ and sensitivity thereof of Antenna I of Section III: (a) high-fidelity EM model reflection response (-o-o) and low-fidelity EM model response (—); (b) sensitivity w.r.t. selected antenna parameters: high-fidelity EM model (··o··o··, - o - o, —o—o)) and low-fidelity model (·····, - - -, —).

The low-fidelity model simulation time is shorter by a factor of around 2.5 as compared to the high fidelity ones. For the algorithms using variable-fidelity models (Algorithms 2 and 4), the high-fidelity model was evaluated only around 13 times for all cases. As shown in Table I, the variable-fidelity approach allows for achieving good design quality and significant cost savings by a factor of around two. For Algorithm 4 (proposed in this work), the savings are also due to limiting the amount of FD, and the reduction of the overall cost is as high as four times for the Antenna II. The design quality is almost the same for Algorithms 2 and 3 for all benchmark cases. Combining both mechanisms as implemented in Algorithm 4 leads for certain quality degradation (by 0.8 dB and 0.7 dB, for Antennas I and II, respectively). For Antenna III, the degradation is higher, and it equals 2 dB. Note that such a considerable cost reduction was achieved despite the fact that the time evaluation ratio between the high- and low-fidelity model is less than three. In many cases, that ratio can be made much higher, consequently implying even more significant cost savings.



(a) (b) (c)

Fig. 2. Benchmark antennas: (a) Antenna I [6], (b) Antenna II [7], and (c) Antenna III [8]. Ground plane marked using light gray shade.



(a) (b) (c)

Fig. 3. Initial (- - -) and optimized (—) responses of the antennas found using the proposed variable-fidelity algorithm, shown for the representative runs of the procedure: (a) Antenna I, (b) Antenna II, and (c) Antenna III. Horizontal lines mark the design specifications.

TABLE I. Optimization Results and Benchmarking

Algorithm		Antenna I			Antenna II			Antenna III		
		Cost$	max $\|S_{11}\|$ [dB]*	Time# [min]	Cost$	max $\|S_{11}\|$ [dB]*	Time# [min]	Cost$	max $\|S_{11}\|$ [dB]*	Time# [min]
1	Fine	97.6	–11.9	277.5	111.2	–14.9	389.2	111.0	–13.9	455.1
2	Coarse	60.0	–11.8	119.8	97.2	–14.8	199.5	109.2	–13.7	199.2
	Fine	13.9			13.4			14.4		
3	Fine	46.1	–11.4	135.2	58.6	–14.7	205.0	68.7	–13.5	281.7
4	Coarse	36.4	–11.1	90.5	45.4	–14.2	96.4	58.6	–11.9	133.9
	Fine	14.5			12.7			14.3		

Algorithms: 1 – reference (high-fidelity model only), 2 – reference (variable-fidelity models), 3 – gradient monitoring (high-fidelity model only), 4 – proposed framework.
$ Number of EM simulations averaged over 10 algorithm runs (random initial points);
* Maximum |S11| within UWB frequency range (averaged over 10 algorithm runs).
# Overall optimization time.

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