Space mapping optimization of microwave circuits exploiting surrogate models

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ABSTRACT

A powerful new Aggressive Space Mapping optimization algorithm is presented. It draws upon recent developments in both surrogate-based optimization and microwave device neuromodeling. Our surrogate formulation (new to microwave engineering) exploits, in a novel way, a linear frequency-space mapping. This is a powerful approach to severe response misalignments.

INTRODUCTION

We present a novel Aggressive Space Mapping algorithm for microwave circuit optimization. It integrates, for the first time, two distinct optimization approaches: Space Mapping (SM) optimization [1] and surrogate-based optimization [2]. Both approaches aim at efficiently optimizing an accurate and time-intensive “fine” model, e.g., a full-wave electromagnetic simulator. SM exploits the existence of a less accurate but fast “coarse” model. It formulates the design problem as a system of nonlinear equations. On the other hand, surrogate-based optimization, new to the microwave arena, exploits an approximate model iteratively in solving the original design problem.

Our algorithm combines both approaches. The original design problem is solved using an approximate surrogate model. This model is a convex combination of a mapped coarse model and a linearized fine model. The accuracy of the surrogate model is improved in every iteration. Recent developments in Space Mapping-based Neuromodeling (SMN) [3] exploit frequency-sensitive mappings. We integrate this concept, in a novel way, with SM optimization. In each iteration, a linear frequency-space mapping is exploited in constructing the mapped coarse model. During the optimization iterates, the coarse and fine models are simulated over different sets of frequencies. The algorithm is demonstrated through the design of a high temperature superconducting (HTS) filter [4].

SPACE MAPPING OPTIMIZATION VS. OPTIMIZATION VIA SURROGATES [1, 2]

We denote the fine model responses at a point \( x_f \in \mathbb{R}^{n_{f \text{d}}} \) and frequency \( \omega \) by \( R_f(x_f, \omega) \in \mathbb{R}^{N_{f \omega}} \). These responses may include the real and imaginary parts of \( S_{11} \), etc. The response vector \( R_f(x_f) \in \mathbb{R}^{m_{f \text{d}}} \) denotes the responses over all the \( N_{f \omega} \) simulation frequencies where \( m=N_f N_{f \omega} \). The original design problem is

\[
    x_f^* = \arg \min_{x_f} U(R_f(x_f)) \tag{1}
\]

where \( U \) is the objective function and \( x_f^* \) is the optimal fine model design. Solving (1) using
direct optimization methods can be prohibitive due to the model’s intensive simulation time.

SM optimization exploits the existence of a fast but less accurate “coarse” model of the circuit. We denote by \( x_c \in \mathbb{R}^{\text{mod}} \) and \( R_c(x_c) \in \mathbb{R}^{\text{mod}} \) a coarse model point and the corresponding response, respectively. SM establishes a mapping \( x_c = P(x_f) \) between the two spaces such that \( R_f(x_f) = R_c(x_c) \) [1]. The space-mapped design \( x_f \) is a solution of the nonlinear system

\[
f(x_f) = P(x_f) - x_c^* = 0
\]  

(2)

where \( P(x_f) \) is approximated through Parameter Extraction (PE) and \( x_c^* \) is the optimal coarse design.

Previous SM-based optimization algorithms solve (2) iteratively. Let \( x_f^{(i)} \) be the \( i \)th iterate in the solution of (2). The original ASM algorithm utilizes a quasi-Newton step. Our TRASM algorithm minimizes \( \| f(x_f^{(i)}) \| \) using least squares within a trust region.

Here, a time-intensive model is optimized using a “surrogate” model. We denote the surrogate model in the \( i \)th iteration by \( R_f^{(i)}(x_f) \in \mathbb{R}^{\text{mod}} \).

The step taken is obtained by solving

\[
h^{(i)} = \arg \min_{h^{(i)}} U(R_f^{(i)}(x_f^{(i)} + h^{(i)})) \quad \| h^{(i)} \| \leq \delta^{(i)}
\]  

(3)

where \( \delta^{(i)} \) is the trust region size. The point \( x_f^{(i)} + h^{(i)} \) is then validated using fine model simulation. It is accepted if it improves the desired fine model objective function. Otherwise, the accuracy of \( R_f^{(i)}(x_f) \) should be improved using fine model validations. Additional fine model simulations may be generated to improve the surrogate model in certain directions of the parameter space.

**OUR SURROGATE MODEL**

In the \( i \)th iteration, our algorithm utilizes a surrogate model expressed as a convex combination between a linearized fine model (LFM) and a mapped coarse model (MCM) \( R_m^{(i)}(x_f) \). It is given by

\[
R_f^{(i)}(x_f) = \lambda^{(i)} R_m^{(i)}(x_f) + (1 - \lambda^{(i)}) (P_f(x_f) + J_f \Delta x_f).
\]  

(4)

where \( J_f^{(i)} \) is an approximation to the Jacobian of fine model responses at \( x_f^{(i)} \) and \( \Delta x_f = x_f - x_f^{(i)} \). The parameter \( \lambda^{(i)} \) determines which of the models LFM or MCM is favored.

The MCM utilizes the linear frequency-space mapping

\[
R_f(x_f, \omega_j) = R_m^{(i)}(x_f, \omega_j) = R_f^{(i)}(x_f, \omega_j), \quad j = 1, 2, \ldots, N_\omega
\]  

(5)

where

\[
\begin{bmatrix}
P_f^{(i)}(x_f, \omega_j) \\
P_m^{(i)}(x_f, \omega_j)
\end{bmatrix} =
\begin{bmatrix}
B^{(i)} \\
s^{(i)} \\
t^{(i)}
\end{bmatrix}
\begin{bmatrix}
\Delta x_f \\
\omega_j
\end{bmatrix} +
\begin{bmatrix}
c^{(i)} \\
\gamma^{(i)}
\end{bmatrix},
\]  

(6)

The parameters \( B^{(i)} \in \mathbb{R}^{\text{mod}}, s^{(i)} \in \mathbb{R}^{\text{mod}}, t^{(i)} \in \mathbb{R}^{\text{mod}}, c^{(i)} \in \mathbb{R}^{\text{mod}}, \sigma^{(i)} \in \mathbb{R}^{\text{bd}}, \text{and } \gamma^{(i)} \in \mathbb{R}^{\text{bd}} \) are the mapping parameters. \( \omega_j \) is the \( j \)th simulation frequency, \( j = 1, 2, \ldots, N_\omega \). Here, a fine model point \( x_f \) and frequency \( \omega_j \) correspond to a coarse point \( P_f^{(i)}(x_f, \omega_j) \) and frequency \( P_m^{(i)}(x_f, \omega_j) \).

The mapping parameters of (6) are obtained so that the MCM approximates the fine model over a region of fine model parameters and frequency. They are obtained by the optimization procedure

\[
\arg \min_{B, s, t, c, \sigma, \gamma}
\begin{bmatrix}
e_1^T \\
e_2^T \\
\vdots \\
e_{N_P}^T
\end{bmatrix}
\]

(7)

\[
e_1 = R_m^{(i)}(x_f^{(k)}) - R_f(x_f^{(k)}) \forall x_f^{(k)} \in \nu^{(i)}
\]  

(8)
where \( V^{(i)} \) is a set of fine model points whose cardinality is \( |V^{(i)}| = N_p \) and \( e \in \mathbb{R}^{m0} \). \( V^{(i)} \) is mainly composed of a subset of previously simulated points. It contains points that are within an \( \alpha \)-neighborhood of \( x_f^{(i)} \) and sufficiently cover this neighborhood. Additional points may be simulated by the algorithm. This occurs if the algorithm fails to make a successful iteration and the previously simulated fine points do not adequately cover the \( \alpha \)-neighborhood.

**THE ALGORITHM**

The \( i \)th iteration of the algorithm proceeds as follows. First, the set \( V^{(i)} \) is constructed. The mapping parameters are then estimated using the optimization procedure (7)-(8). The step \( h^{(i)} \) is obtained by solving (3), where the surrogate model is given by (4). Notice that (3) utilizes only coarse model simulations and can be solved by traditional optimization methods.

\( h^{(i)} \) is accepted if it improves the objective function. Otherwise, it is rejected. The parameters \( J_f^{(i)}, \delta^{(i)} \) and \( \lambda^{(i)} \) are updated in each iteration. Broyden's formula [5] is used to update \( J_f^{(i)} \). Initially, we set \( J_f^{(0)} = J_f^0 \), the Jacobian of the coarse model response at \( x_c \).

The trust region \( \delta^{(i)} \) is updated based on how the actual reduction \( r_a \) in \( U \) matches the predicted reduction \( r_p \). The ratio

\[
\rho = \frac{r_a}{r_p} = \frac{U(R_f(x_f^{(i)})) - U(R_f(x_f^{(i)} + h^{(i)}))}{U(R_f(x_f^{(i)})) - U(R_f(x_f^{(i)} + h^{(i)}))} \tag{9}
\]

is thus evaluated at the end of each iteration. If \( \rho \geq 0.75 \), the surrogate model has good accuracy and we set \( \delta^{(i+1)} = \pi_1 \delta^{(i)} \), \( \pi_1 > 1.0 \). If \( \rho \leq 0.10 \), we set \( \delta^{(i+1)} = \pi_2 \delta^{(i)} \), \( 0 < \pi_2 < 1.0 \). Otherwise, we set \( \delta^{(i+1)} = \delta^{(i)} \). \( \lambda^{(i)} \) is updated to favor the more accurate model, either the LFM or the MCM. It is initialized by \( \lambda^{(0)} = 1.0 \). The actual update utilized is

\[
\lambda^{(i+1)} = \frac{\|E_i^{(i)}\|}{\|E_i^{(i)}\| + \|E_m^{(i)}\|} \tag{10}
\]

where \( E_i^{(i)} = R_m^{(i)}(x_f^{(i)} + h^{(i)}) - R_f(x_f^{(i)} + h^{(i)}) \) and \( E_m^{(i)} = R_f(x_f^{(i)} + J_f^{(i)} h^{(i)}) - R_f(x_f^{(i)} + h^{(i)}) \) define the prediction error using the MCM and the LFM, respectively. The algorithm terminates if \( n + 1 \) consecutive unsuccessful iterations are carried out or if \( \|h^{(i)}\| \) becomes sufficiently small.

One iteration of the algorithm is shown in Fig. 1.

**THE HTS FILTER**

We consider the design of an HTS filter [4] (see Fig. 2). The design specifications are

\[
|S_{21}| \leq 0.05 \text{ for } \omega \leq 3.967 \text{ GHz and } \\
|S_{21}| \geq 0.95 \text{ for } 4.008 \text{ GHz} \leq \omega \leq 4.058 \text{ GHz} \tag{11}
\]

The design parameters are \( L_1, L_2, L_3, S_1, S_2 \) and \( S_3 \). We take \( L_0 = 50 \text{ mil} \) and \( W = 7 \text{ mil} \). The coarse model exploits the empirical models of microstrip lines, coupled lines and open stubs available in OSA90/hope [6]. The fine model employs Sonnet's *em* [7] through Empipe [6].

The fine model is simulated at 16 frequency points. We utilize the real and imaginary parts of both \( S_{11} \) and \( S_{21} \) in the optimization procedure (7)-(8). The initial trust region is \( \delta^{(0)} = 0.20 \|x_c^{(0)}\| \). The interpolation option of
CONCLUSIONS

We present a breakthrough algorithm for efficient optimization of microwave circuits. The algorithm integrates, for the first time, SM optimization with optimization via surrogates. It exploits a novel surrogate formulation in the form of a convex combination of a mapped coarse model and a linearized fine model. The MCM model utilizes, in a novel way, a frequency-space mapping. During optimization, the coarse and fine models are simulated over different frequency ranges. The algorithm is successfully illustrated through the design of a microwave filter.

REFERENCES


