New Developments in Space Mapping CAD Technology

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***Abstract*—We review the state of the art in space mapping (SM) and the SM-based surrogate (modeling) concepts. We describe the input, implicit and output SM techniques. We present an SM framework and its applications in engineering modeling and design optimization. Significant examples of recent implementations of SM are reviewed.**

***Index Terms*—CAD, EM simulation, engineering optimization, parameter extraction, surrogate modeling, space mapping**

I. Introduction

Engineers continue to benefit from optimization technologies in device, component and system modeling and CAD [1]. The goal for component design is to determine the physical parameters of the components to satisfy design specifications. Traditional optimization techniques [2, 3] directly exploit simulated responses and possible response derivatives.

Circuit-theory based CAD tools using empirical device models are typically fast. Electromagnetic (EM) simulators need to be exploited but the higher the simulation fidelity (accuracy) the more expensive the direct optimization process.

Schemes are desirable that combine the speed and maturity of circuit simulators with the accuracy of EM solvers. This issue is addressed by the exploitation of iteratively refined surrogates of fine, accurate or high-fidelity models, and the implementation of space mapping (SM) methodologies. Through an SM, a suitable surrogate can be obtained: faster than the "fine" model and at least as accurate as the "coarse" model on which it is based (see Fig. 1). We list models and their classification in Table I.

We review here the state of the art of SM [4]: the original SM [5], the aggressive SM (ASM) [6], implicit SM (ISM) [7] and recent input/output SM [8] optimization and modeling. We indicate the latest implementations of SM technology.

II. Review of Space Mapping

The first algorithm (original SM) was introduced in 1994 [5]. The ASM approach [6] eliminates the simulation overhead of the original SM [5] by immediately exploiting each fine model iterate. Implicit SM (ISM) selects auxiliary (preassigned) parameters, e.g., dielectric constant and substrate height, to match the coarse and fine models. They are varied in the coarse model only. See Fig. 2. With these parameters fixed, the calibrated coarse model (the surrogate) is reoptimized and the optimized parameters are assigned to the fine model. This process repeats until the fine model response is sufficiently close to the target response. In addition to preassigned parameters in ISM, the surrogate can be augmented by input SM

TABLE I
Classification of Models

Model	Classification
companion	coarse
low fidelity/resolution	coarse
high fidelity/resolution	fine
empirical	coarse
simplified physics	coarse
physics-based	coarse or fine
physically expressive	coarse
device under test	fine
electromagnetic	fine or coarse
simulation	fine or coarse
computational	fine or coarse
mapped coarse model	surrogate
tuning-parameter-augmented fine-model iterate (with internal tuning ports)	surrogate
optimization process	fine

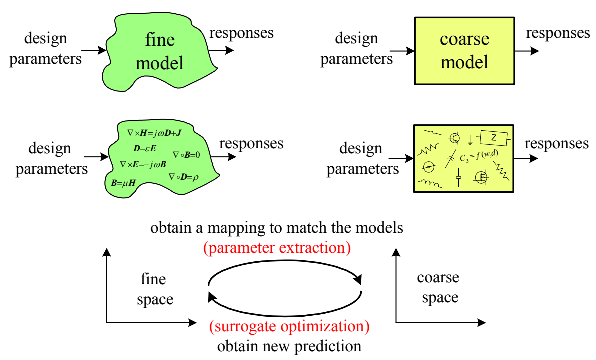

Fig. 1. Linking companion coarse (empirical) and fine (EM) models through a mapping.

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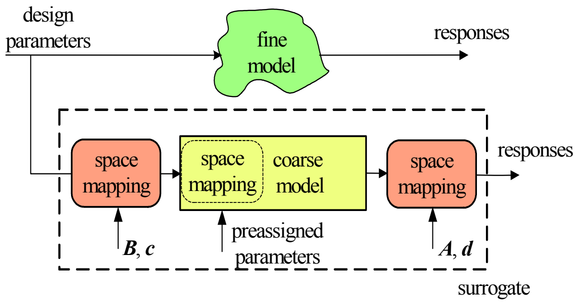


Fig. 2. Fine model, coarse model and surrogate [8].

[8] with mapping parameters ***B***, ***c*** to transfer the design parameters, output SM [8] with mapping parameters ***A***, ***d*** to transfer the responses. Implicit, input and output mapping can be combined to obtain an accurate surrogate as in Fig. 2.

III. Space Mapping Framework

A. An SM Framework for Design

Step 1 Select the fine and coarse models, decide on and initialize mapping parameters ***B***, ***c***, ***A***, ***d***, or preassigned parameters.
Step 2 Optimize the coarse model (initial surrogate) w.r.t. design parameters.
Step 3 Simulate the corresponding fine model
Step 4 Terminate if a stopping criterion is satisfied, e.g., response meets specifications.
Step 5 If necessary, match the surrogate to the fine model (parameter extraction) and/or update the surrogate.
Step 6 Optimize the surrogate and/or predict the next fine model iterate.

B. An SM Framework for Modeling

Step 1 Select the fine and coarse models, decide on and initialize mapping parameters ***B***, ***c***, ***A***, ***d***.
Step 2 Generate the base points and multiple test points.
Step 3 Simulate the fine model at all the base points.
Step 4 Match the surrogate to the fine model (parameter extraction) using all the base points simultaneously.
Step 5 Test the SM-based surrogate model at the test points.
Step 6 If necessary, interpolate the surrogate responses for arbitrary frequency values.

We show the flowcharts in Figs 3 and 4, respectively. The frameworks require interaction between coarse models, fine models and optimization tools. Design values and frequency data have to be sent to different simulators and corresponding responses have to be retrieved.

Agilent ADS provides "coarse" models and optimization tools. Its component *S*-parameter file enables *S*-parameters to be imported in Touchstone file format from different EM simulators (fine model) such as Sonnet's ***em*** and Agilent Momentum. Imported *S*-parameters can be matched (parameter extraction) with the ADS circuit (coarse) model responses. Our framework uses the following ADS key components in implementing SM techniques:

VAR: variables and equation component;
OPTIM: nominal optimization setup;
GOAL: optimization goal;
S-PARAMETERS: ADS *S*-parameter simulation frequency sweep options;
S*n*P: *n*-port *S*-parameter file.

IV. Space Mapping Examples

A. HTS Coupled-line Microstrip Filter Design [7]

ISM is effective for microwave modeling and design using full-wave EM simulators. There are no matrices to keep track of. A high-temperature superconducting (HTS) coupled-line microstrip filter is designed within Agilent ADS [9] and Momentum [10] or Sonnet's ***em*** [11] using ISM.

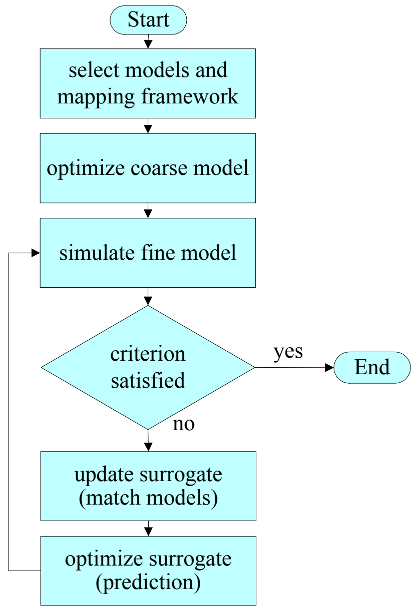


Fig. 3. A space mapping framework for design.

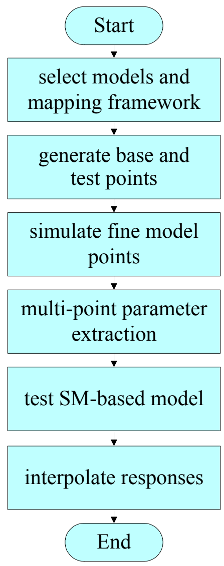


Fig. 4. A space mapping framework for modeling [8].

Fig. 5 shows the HTS filter [6,12]. A lanthanum aluminate substrate is used. Design parameters are $\boldsymbol{x}_f = [L_1\ L_2\ L_3\ S_1\ S_2\ S_3]^T$. L_0 = 50 mil, thickness H = 20 mil, W = 7 mil, dielectric constant ε_r = 23.425, loss tangent = 3×10^{-5}; the metalization is considered lossless. Design specifications are $|S_{21}| \geq 0.95$ for 4.008 GHz $\leq \omega \leq$ 4.058 GHz; $|S_{21}| \leq 0.05$ for $\omega \leq$ 3.967 GHz and $\omega \geq$ 4.099 GHz.

Our Agilent ADS [9] coarse model consists of empirical models for single and coupled microstrip transmission lines, with ideal open stubs. Fig. 4 indicates a symmetrical structure. The fine model is simulated first by Agilent Momentum [10]. The algorithm requires 2 iterations (3 fine model simulations). Sonnet ***em*** [11] has also been used as a fine model. Two fine model simulations are used to reach the solution.

B. Six-Section H-plane Waveguide Filter Design [13]

Another SM example is the six-section H-plane waveguide filter [14,15] shown in Fig. 6(a). We use the ADS framework exploiting implicit SM and final response tune (so called RRSM, a special case of output space mapping) to design an H-plane filter. We employed two iterations of implicit SM to drive the design to be close to the optimal solution and subsequent two iterations of implicit SM with response tune. The design parameters are the lengths and widths: L_1, L_2, L_3, W_1, W_2, W_3, W_4. Design specifications are $|S_{11}| \leq 0.16$ for frequency range 5.4-9.0 GHz; $|S_{11}| \geq 0.85$ for frequency $\omega \leq$ 5.2 GHz; $|S_{11}| \geq 0.5$, for frequency $\omega \geq$ 9.5 GHz.

We use 23 sample points. A waveguide with a cross-section of 1.372 × 0.622 inches (3.485 × 1.58 cm) is used. The six sections are separated by seven H-plane septa, which have a finite thickness of 0.02 inches (0.508 mm). The coarse model consists of lumped inductances and waveguide sections. The equivalent inductive susceptance corresponding to an H-plane septum is calculated from a simplified formula due to Marcuvitz [16]. The coarse model is simulated using ADS [see Fig. 6(b)].

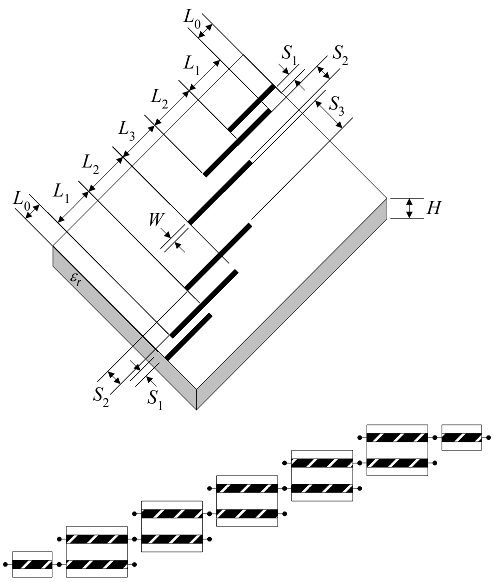
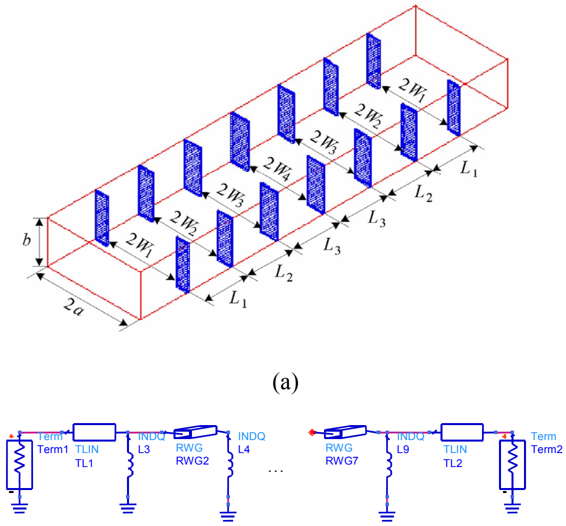


Fig. 5. HTS quarter-wave parallel coupled-line microstrip filter [6,12] and a representation of its coarse model.



(a)

(b)

Fig. 6. (a) Six-section H-plane waveguide filter [14,15] (b) ADS coarse model [13].

We select the waveguide width of each section as the preassigned parameters to calibrate the coarse model. The frequency coefficient of each inductor, for convenience PI, is also harnessed as a preassigned parameter to compensate for the susceptance change. Since no Jacobian is needed, five fine model (Agilent HFSS) simulations are employed.

C. Microstrip Shaped T-junction Modeling [8]

In this example we demonstrate the SM technique for modeling. A shaped T-junction [17] [Fig. 7(a)] is symmetric in the sense that all input lines have the same width w. The fine model is analyzed by Sonnet's ***em*** and the coarse model is composed of empirical models of simple microstrip elements [see Fig. 7(b)] of Agilent ADS. The fine and coarse model parameters are given by $\boldsymbol{x}_f = [w\ w_2\ w_1\ y\ x\ h\ \varepsilon_r]^T$ and $\boldsymbol{x}_c = [w_c\ w_{c2}\ w_{c1}\ y_c\ x_c\ h_c\ \varepsilon_{rc}]^T$. The region of interest is 15mil $\leq h \leq$ 25mil, 5mil $\leq x \leq$ 15mil, 5mil $\leq y \leq$ 15mil, and $8 \leq \varepsilon_r \leq 10$. The frequency range used is 2 GHz to 20 GHz with a step of 2 GHz (10 points). The width w of the input lines is determined in terms of h and ε_r so that the characteristic impedance of the input lines is 50 ohm. The width w_1 is taken as 1/3 of the width w; w_2 is obtained so that the characteristic impedance of the microstrip line after the step connected to port 2 is twice that of the line after the step connected to port 1 [see Fig. 7(b)]. The number of base points is 9 since we have only 4 independent variables $\{h, x, y, \varepsilon_r\}$. The reference point is $\boldsymbol{x}^0$=[21 33 7 10 10 20 9]^T. A statistical analysis shows that an accurate model is obtained.

D. Other Applications

Ismail *et al.* [18] apply SM optimization to design a 5-pole dielectric resonator (DR) loaded filter and a 10-channel output multiplexer. It significantly reduces overall tuning time compared to traditional techniques. Finite-element EM-based simulators are used as a fine model for each multiplexer

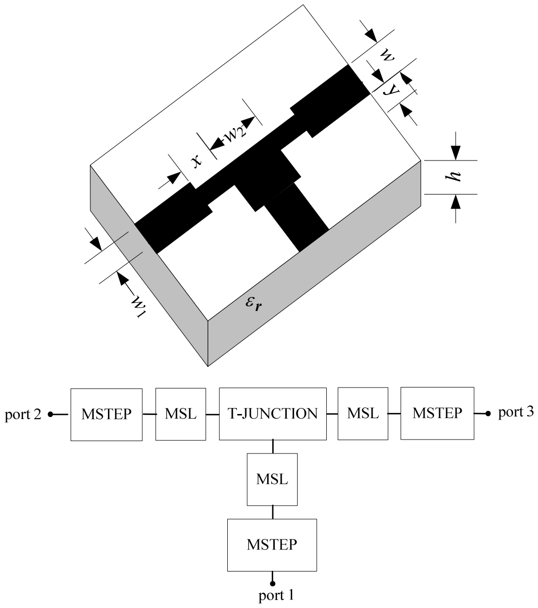


Fig. 7. Microstrip shaped T-junction: (a) the physical structure (fine model) [17]; (b) the coarse model [8,17].

channel, and a coupling matrix representation is used as a coarse model. Fine details such as tuning screws are included in the fine model. The DR filter and multiplexer design parameters are kept bounded during optimization. Sparsity of the mapping between the design parameters and the coupling elements has been exploited.

Rautio [19] efficiently realizes the accuracy of a large number of thin sheets (mimicking the thick metal in planar EM analysis) by introducing a "space mapping" layer into a simple model that can be efficiently analyzed. He introduces a space-mapped two-sheet model for thick metal. The model modifies a "coarse," less accurate, but fast two-sheet model so that it provides the same result as a "fine," accurate but slow extrapolated infinite-sheet model. This thick-metal model is appropriate for tightly coupled lines, especially when the gap is less than the metal thickness. The model is validated for a five-turn spiral inductor on silicon.

Castro *et al.* [20] propose a scheme using multifidelity model interactions. This "multifidelity optimization" (MFO) algorithm takes advantage of the interactions between multifidelity models to develop a dynamic and computational time saving optimization algorithm. First, a direct search method is applied to the high fidelity model over a reduced design space. In conjunction with this search, a specialized oracle is employed to map the design space of this high fidelity model to that of a computationally cheaper low fidelity model using SM techniques. Then, in the low fidelity space, an optimum is obtained using gradient or non-gradient based optimization, and it is mapped back to the high fidelity space.

V. Conclusions

The SM technique and the SM-oriented surrogate (modeling) concept follow the traditional experience and intuition of design engineers. Various SM techniques are reviewed. Frameworks for design and modeling are described. Recent interesting SM applications are outlined. They indicate that SM and its variations can be used in a wide range of application areas.

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