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Space Mapping: A Novel Design and Modeling Methodology

John W. Bandler, *Fellow, IEEE* and Qingsha S. Cheng, *Student Member, IEEE*

***Abstract*—We review the Space Mapping (SM) and the SM-based surrogate (modeling) concepts and their applications in engineering modeling and design optimization. The aim of SM is to achieve a satisfactory solution with a minimal number of computationally expensive "fine" model evaluations. SM procedures iteratively update and optimize surrogates based on a fast physically-based "coarse" model. We review the original, aggressive and implicit SM (ISM) techniques. A "cheese-cutting" problem illustrates the ISM concept. Significant recent practical applications are reviewed.**

***Index Terms*—CAD, design automation, EM simulation, engineering optimization, filter design, optimization, parameter extraction, space mapping**

I. INTRODUCTION

OPTIMIZATION technologies have been used by engineers for device, component and system modeling and CAD for decades [1]. The goal for component design is to determine physical parameters of 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 fast. Electromagnetic (EM) simulators should be exploited in the optimization process but the higher the simulation fidelity (accuracy) the more expensive direct optimization.

Schemes combining the speed and maturity of circuit simulators with the accuracy of EM solvers are desirable. The exploitation of iteratively refined surrogates of fine, accurate or high-fidelity models, and the implementation of space mapping (SM) methodologies address this issue. Through a space mapping, 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): Table I shows the classification of the models.

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

II. REVIEW OF SPACE MAPPING

The first algorithm (original SM) was introduced in 1994 [5]. A linear mapping is assumed between the coarse and fine parameter spaces. It is evaluated by a least squares solution of the linear equations resulting from associating corresponding points (data) in the two spaces. Hence, the surrogate is a piecewise linearly mapped coarse model.

The ASM approach [6] eliminates the simulation

TABLE I
CLASSIFICATION OF MODELS

Model	Classification
Companion	coarse
Low Fidelity	coarse
High Fidelity	fine
Empirical	coarse
Physics-based	coarse or fine
Device under Test	fine
Electromagnetic	fine or coarse
Simulation	fine or coarse
Computational	fine or coarse
Mapped Coarse Model	surrogate

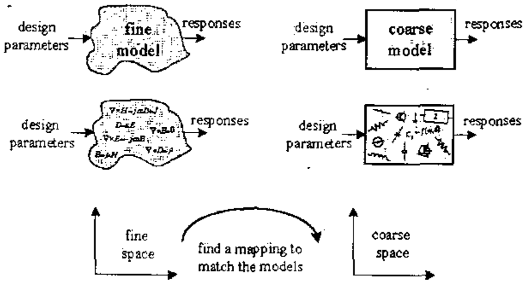

Fig. 1. Linking companion coarse (empirical) and fine (EM) models through a mapping.

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J.W. Bandler is with Bandler Corporation, P.O. Box 8083, Dundas, ON, Canada L9H 5E7.

J.W. Bandler and Q.S. Cheng are with the Simulation Optimization Systems Research Laboratory and Department of Electrical and Computer Engineering, McMaster University, Hamilton, ON, Canada L8S 4K1.

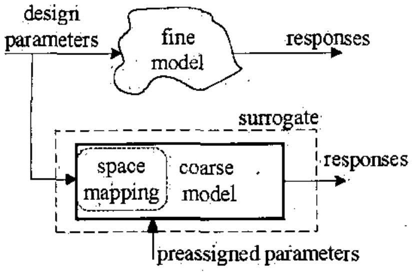

Fig. 2. Illustration of ISM

overhead of the original SM [5] by immediately exploiting each fine model iterate. This iterate, determined by a quasi-Newton step, in effect optimizes the (current) surrogate model.

III. IMPLICIT SPACE MAPPING OPTIMIZATION [7]

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. The idea of using preassigned parameters was introduced in [8] within an expanded SM design framework.

The ISM algorithm is outlined as follows.

Step 1 Select candidate preassigned parameters.
Step 2 Set $j = 0$ and initialize.
Step 3 Obtain the optimal (calibrated) coarse model parameters.
Step 4 Assign the coarse model parameters to the fine model parameters.
Step 5 Simulate the fine model.
Step 6 Terminate if a stopping criterion (e.g., response meets specifications) is satisfied.
Step 7 Calibrate the coarse model by extracting (parameter extraction step) the preassigned parameters.
Step 8 Increment j and go to Step 3.

The ISM process can be demonstrated by a simple example, the cheese-cutting problem, depicted in Fig. 3. The goal is to deliver a segment of cheese of *weight* 30 units (target "response"). The "coarse" model is a cuboidal block (the top block in Fig. 3). A unity density and a cross-section of 3 by 1 units are assumed. The "fine" model has a corresponding cuboidal shape with a defect of 6 missing units of *weight* (the lower block in Fig. 3).

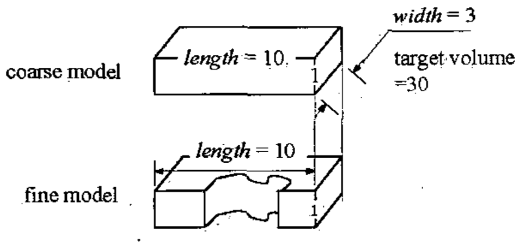

Fig. 3. Coarse and fine models for the "cheese-cutting" problem in the first iteration.

We select the width of the coarse model as a preassigned parameter (Step 1). We set the counter to 0 and start the ISM algorithm (Step 2). We optimize the coarse model (Step 3). A *length* of 10 units will give 30 units of *weight* for the coarse model. An unbiased cut of the same length (Step 4) in the fine model weighs 24 units (Step 5, fine model evaluation). The specification is not satisfied (Step 6). The *width* (preassigned parameter) of the (coarse) model is shrunk to 2.4 units to match the fine model weight (Step 7, parameter extraction). We increase the counter (Step 8) and go back to Step 3. A reoptimization of the *length* of the calibrated coarse model (the surrogate) is performed. The new *length* of 12.5 units is assigned (Step 4) to the irregular block (fine model). We continue until the irregular block is sufficiently close to the desired *weight* of 30 units. The error reaches 1% after 3 iterations.

ISM is effective for microwave modeling and design using full-wave EM simulators. This technique is more easily implemented than [8]. 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].

Fig. 4 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). The total time taken is 26 min (one fine model simulation takes approximately 9 min on an Athlon 1100 MHz). Sonnet ***em*** [11] has also been used as a fine model. It takes 74 minutes to complete a sweep on an Intel P4 2200 MHz machine. Two fine model simulations are used to reach the solution.

IV. IMPLEMENTATION AND APPLICATIONS

A. RF and Microwave Implementation

The required interaction between coarse models,

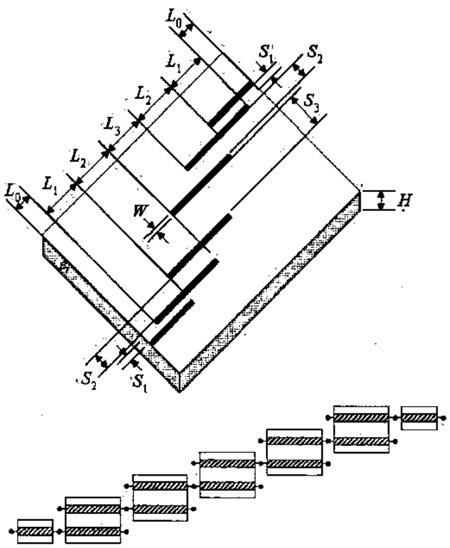

Fig. 4. HTS quarter-wave parallel coupled-line microstrip filter [6,12] and a representation of its coarse model.

fine models and optimization tools can make SM difficult to automate within existing simulators. Design or preassigned parameter values and frequency data have to be sent to different simulators and corresponding responses retrieved.

Various software packages have been investigated. Packages such as OSA90 or Matlab can provide coarse model analyses as well as optimization tools. Empipe and Momentum driver [13] have been designed to drive and communicate with Sonnet's ***em*** and Agilent Momentum [10] as fine models. ASM optimization of 3D structures [14] has been automated using a two-level Datapipe architecture of OSA90: the algorithm carries out the nested optimization loops in two separate processes.

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. We have developed an ADS design framework [15] which makes these major steps of SM friendly for engineers to apply.

B. Major Recent Contributions to Space Mapping

Leary *et al.* [16] apply the SM technique in civil engineering structural design. Devabhaktuni *et al.* [17] propose a technique for generating microwave neural-models of high accuracy using less accurate data. Swanson, Jr. *et al.* [18] introduce a design approach based on the SM concept and commercial FEM solvers. Harscher *et al.* [19] use a technique combining EM simulations with a minimum prototype filter network (surrogate). Draxler [20] introduces a methodology for CAD of integrated passive elements on Printed Circuit Board (PCB) incorporating Surface Mount Technology (SMT). Ye and Mansour [21] apply SM steps to reduce the simulation overhead required in microstrip filter design. Snel [22] proposed the SM technique in RF filter design for power amplifier circuits. Pavio *et al.* [23] apply typical SM techniques in optimization of high-density multilayer RF and microwave circuits. Lobeek [24] demonstrates the design of a DCS/PCS output match of a cellular power amplifier using SM. Safavi-Naeini *et al.* [25] consider a 3-level design methodology for complex RF/microwave structure using an SM concept. Pelz [26] applies SM in realization of narrowband coupled resonator filter structures. Wu *et al.* [27] present an explicit knowledge embedded space mapping optimization technique. Wu *et al.* [28] propose a concept called the dynamic coarse model and apply it to the optimization design of LTCC multilayer RF circuits with the ASM technique. Steyn *et al.* [29] consider the design of irises in multi-mode coupled cavity filters. Soto *et al.* [30] apply the ASM procedure to build an automated design of inductively coupled rectangular waveguide filters. Redhe *et al.* [31] apply the SM technique and surrogate models together with response surfaces to structural optimization of crashworthiness problems. Choi *et al.* [32] utilize SM to design magnetic systems. Feng [33] *et al.* apply the SM technique for design optimization of antireflection coatings for photonic devices such as semiconductor optical amplifiers. Feng and Huang [34] employ a generalized space mapping technique for modeling and simulation of photonic devices. Ismail *et al.* [35] apply SM optimization with FEM (fine model) to design a 5-pole dielectric resonator loaded filter and a 10-channel output multiplexer. Gentili *et al.* [36] implement an accurate design of microwave comb filters using SM. Zhang *et al.* [37] introduce a new Neuro-SM approach for nonlinear device modeling and large signal circuit simulation.

V. CONCLUSIONS

The SM technique and the SM-oriented surrogate (modeling) concept follow the traditional experience and intuition of engineers. The aim and advantages of SM are described. Interesting SM algorithms and applications are reviewed. They indicate that exploitation of properly managed "space mapped" surrogates delivers significant efficiency in RF and microwave engineering design.

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