Space Mapping: Engineering Modeling And Optimization Exploiting Surrogates

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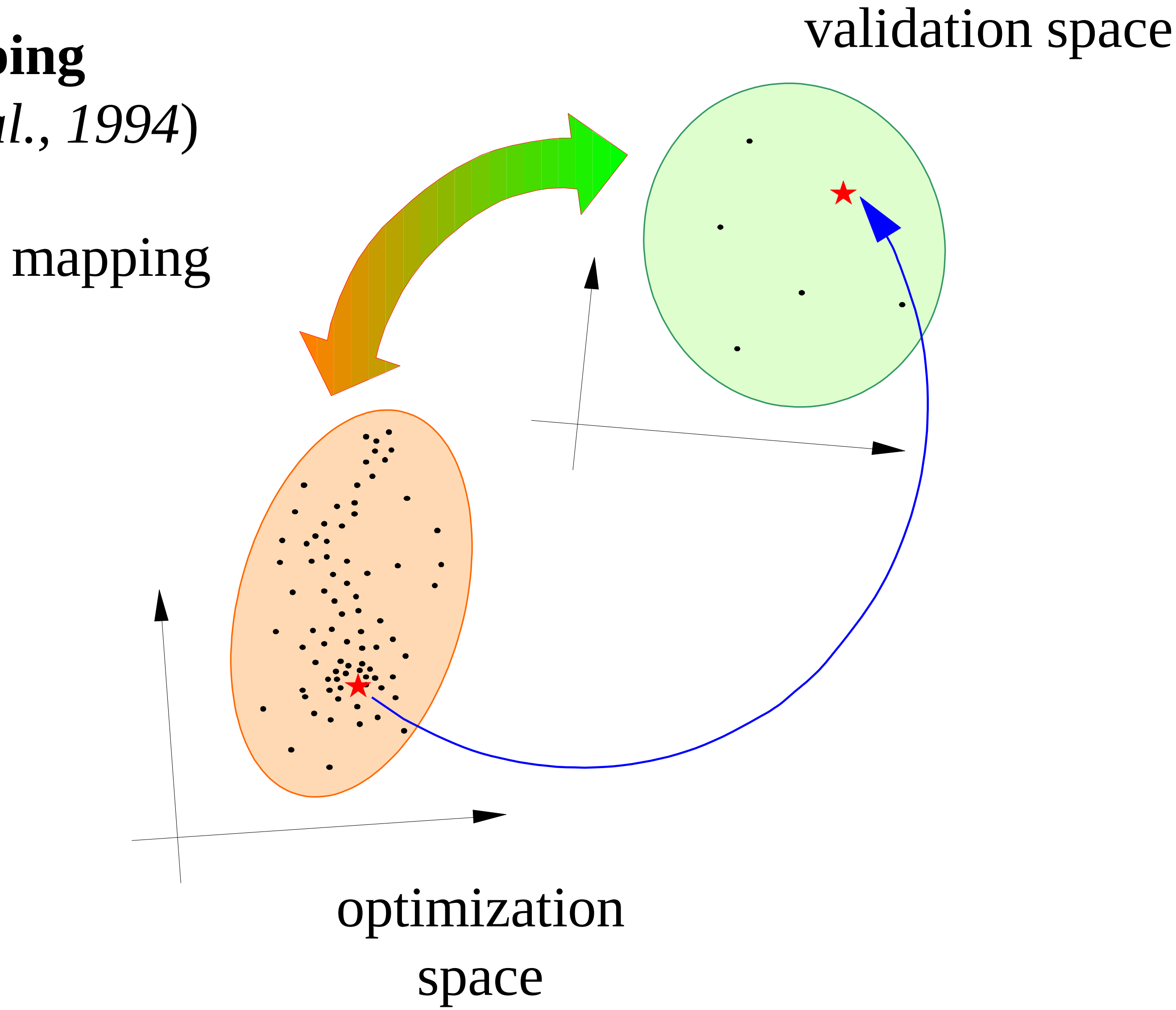
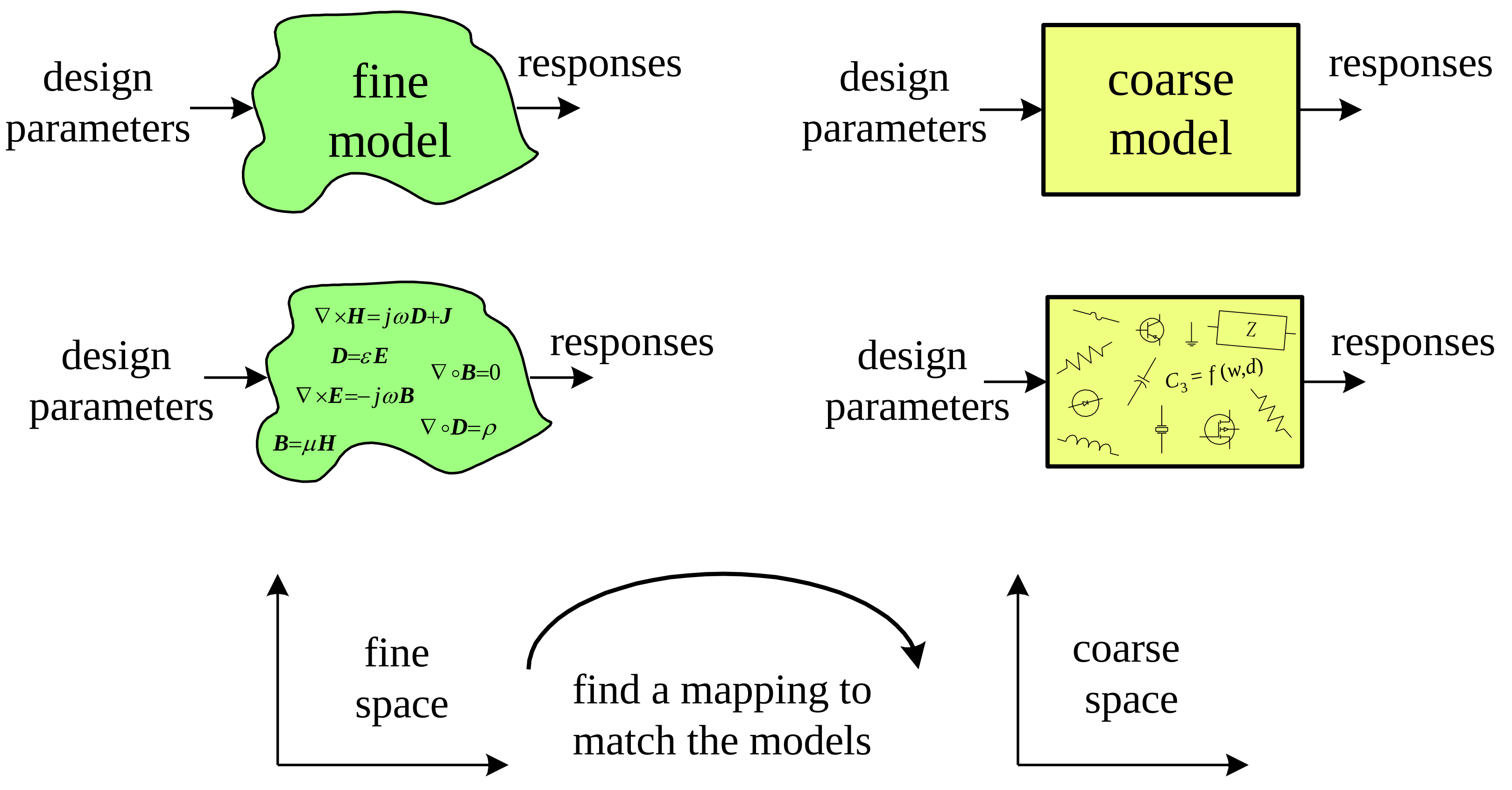
Space Mapping

(*Bandler et al., 1994*)

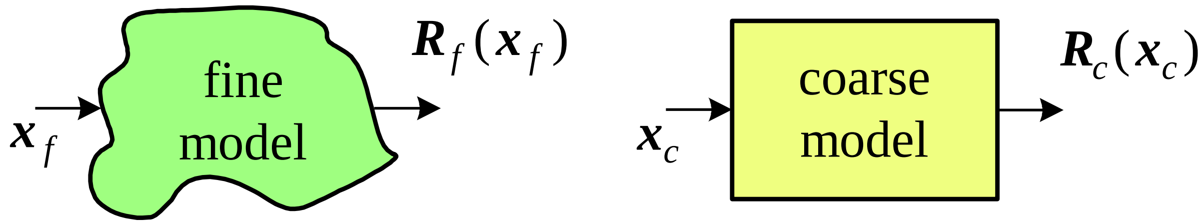


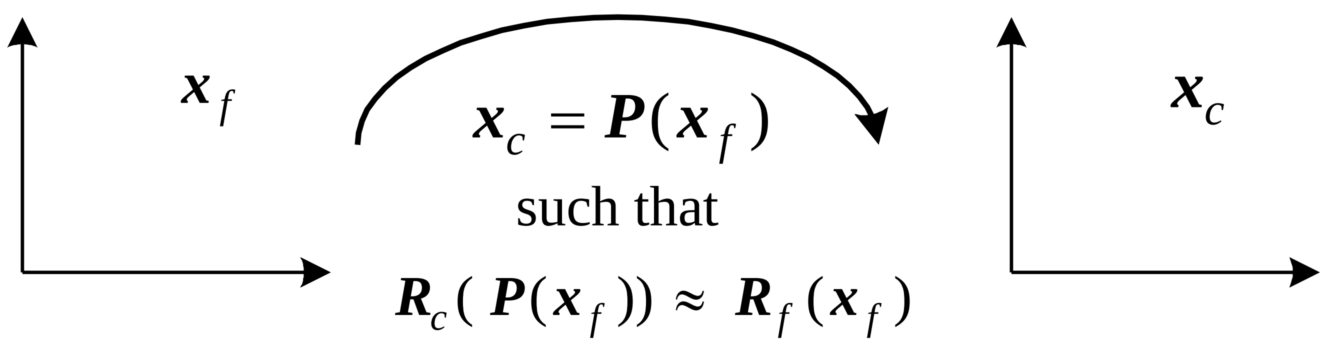
Linking Companion Coarse (Empirical) and Fine (EM) Models



The Space Mapping Concept

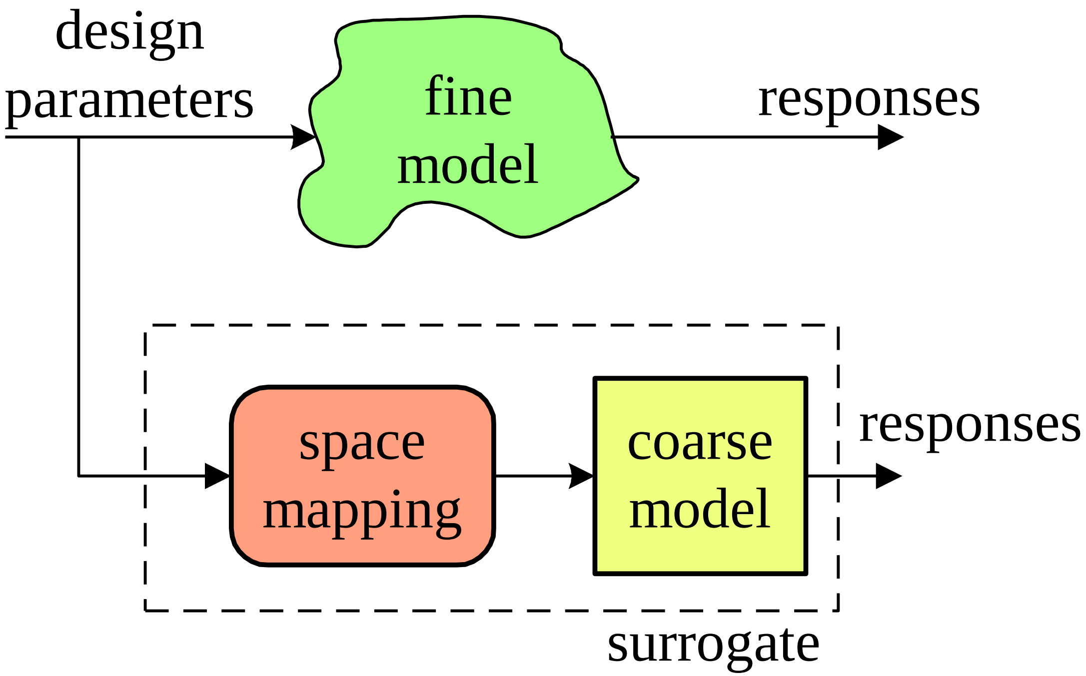
(Bandler et al., 1994-)





Explicit Space Mapping Concept

(*Bandler et al., 1994-*)



Space Mapping: a Glossary of Terms

Space Mapping	transformation, link, adjustment, correction, shift (in parameters or responses)
Coarse Model	simplification or convenient representation, companion to the fine model, auxiliary representation, cheap model
Fine Model	accurate representation of system considered, device under test, component to be optimized, expensive model

Space Mapping: a Glossary of Terms

Surrogate	model, approximation or representation to be used, or to act, in place of, or as a substitute for, the system under consideration
	mapped or enhanced coarse model
Surrogate Model	alternative expression for Surrogate
Target Response	response the fine model should achieve, (usually) optimal response of a coarse model, enhanced coarse model, or surrogate

Space Mapping: a Glossary of Terms

Companion	coarse
Low Fidelity/ Resolution	coarse
High Fidelity/ Resolution	fine
Empirical	coarse
Simplified Physics	coarse
Physics-based	coarse or fine
Device under Test	fine
Electromagnetic	fine or coarse
Simulation	fine or coarse
Computational	fine or coarse

Space Mapping: a Glossary of Terms

Parameter (input) Space Mapping	mapping, transformation or correction of design variables
Response (output) Space Mapping	mapping, transformation or correction of responses
Response Surface Approximation	linear/quadratic/polynomial approximation of responses w.r.t. design variables

Space Mapping: a Glossary of Terms

Neuro	implies use of artificial neural networks
Implicit Space Mapping	space mapping when the mapping is not obvious
Not Space Mapping	(usually) space mapping when not acknowledged
Parameter Transformation	space mapping
Predistortion	?

Jacobian-Space Mapping Relationship
(*Bakr et al., 1999*)

through PE we match the responses

$$\boldsymbol{R}_f(\boldsymbol{x}_f) \approx \boldsymbol{R}_c(\boldsymbol{P}(\boldsymbol{x}_f))$$

by differentiation

$$\left(\frac{\partial \boldsymbol{R}_f^T}{\partial \boldsymbol{x}_f}\right)^T \approx \left(\frac{\partial \boldsymbol{R}_c^T}{\partial \boldsymbol{x}_c}\right)^T \cdot \left(\frac{\partial \boldsymbol{x}_c^T}{\partial \boldsymbol{x}_f}\right)^T$$

Jacobian-Space Mapping Relationship
(*Bakr et al., 1999*)

given coarse model Jacobian $\boldsymbol{J}_c$ and space mapping matrix $\boldsymbol{B}$ we estimate

$$\boldsymbol{J}_f(\boldsymbol{x}_f) \approx \boldsymbol{J}_c(\boldsymbol{x}_c)\boldsymbol{B}$$

given $\boldsymbol{J}_c$ and $\boldsymbol{J}_f$ we estimate (least squares)

$$\boldsymbol{B} \approx (\boldsymbol{J}_c^T \boldsymbol{J}_c)^{-1} \boldsymbol{J}_c^T \boldsymbol{J}_f$$

Aggressive Space Mapping Practice—Cheese Cutting Problem

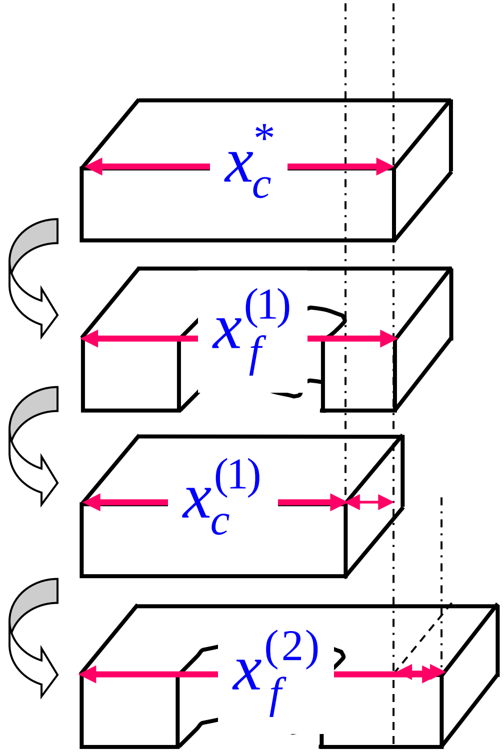
(*Bandler et al., 2002*)

optimal coarse model

initial guess

PE

prediction



$$x_f^{(1)} = x_c^*$$

$$x_f^{(2)} = x_f^{(1)} + P^{-1}(x_c^* - x_c^{(1)})$$

$$x_f^{(2)} = x_f^{(1)} + x_c^* - x_c^{(1)}$$

Interpretation of Space Mapping Optimization

the original optimization problem

$$\boldsymbol{x}^* \triangleq \arg\min_{\boldsymbol{x}} U(\boldsymbol{R}(\boldsymbol{x}))$$

consider $\boldsymbol{R}_c(\boldsymbol{P}(\boldsymbol{x}_f))$ as an “enhanced” coarse model or “surrogate,” then

$$\bar{\boldsymbol{x}}_f = \arg\min_{\boldsymbol{x}_f} U(\boldsymbol{R}_c(\boldsymbol{P}(\boldsymbol{x}_f)))$$

is equivalent to

$$\boldsymbol{f}(\boldsymbol{x}_f) \triangleq \boldsymbol{P}(\boldsymbol{x}_f) - \boldsymbol{x}_c^*, \quad \boldsymbol{f} \rightarrow \boldsymbol{0}$$

Aggressive Space Mapping Approach
(*Bandler et al., 1995*)

iteratively solves the nonlinear system

$$\boldsymbol{f}(\boldsymbol{x}_f) = \boldsymbol{0}$$

the quasi-Newton step $\boldsymbol{h}^{(j)}$ in the fine space is given by

$$\boldsymbol{B}^{(j)}\boldsymbol{h}^{(j)} = -\boldsymbol{f}^{(j)}$$

the next iterate

$$\boldsymbol{x}_f^{(j+1)} = \boldsymbol{x}_f^{(j)} + \boldsymbol{h}^{(j)}$$

Aggressive Space Mapping Approach (continued)

Broyden-like updates (*Bandler et al., 1995*)

$$\boldsymbol{B}^{(j+1)} = \boldsymbol{B}^{(j)} + \frac{\boldsymbol{f}^{(j+1)} - \boldsymbol{f}^{(j)} - \boldsymbol{B}^{(j)}\boldsymbol{h}^{(j)}}{\boldsymbol{h}^{(j)T}\boldsymbol{h}^{(j)}}\boldsymbol{h}^{(j)T}$$

Jacobian based updates (*Bandler et al., 1999, 2002*)

$$\boldsymbol{B} = (\boldsymbol{J}_c^T \boldsymbol{J}_c)^{-1} \boldsymbol{J}_c^T \boldsymbol{J}_f$$

$$\boldsymbol{E} = \boldsymbol{J}_f - \boldsymbol{J}_c \boldsymbol{B}$$

constrained update (*Bakr et al., 2000*)

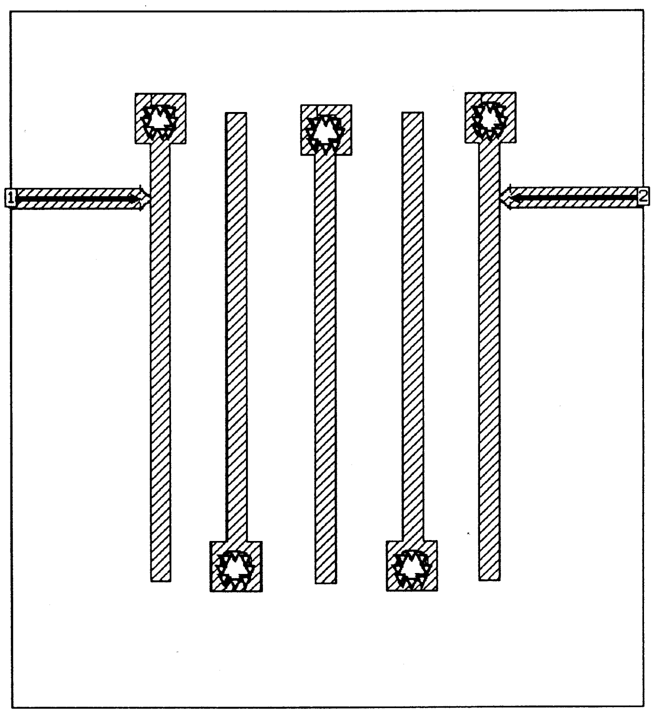
$$\Delta\boldsymbol{B} = \boldsymbol{B} - \boldsymbol{I}$$

$$\boldsymbol{B} = \arg\min_{\boldsymbol{B}} \left\| [\boldsymbol{e}_1^T \cdots \boldsymbol{e}_n^T \quad \eta\Delta\boldsymbol{b}_1^T \cdots \eta\Delta\boldsymbol{b}_n^T]^T \right\|_2^2$$

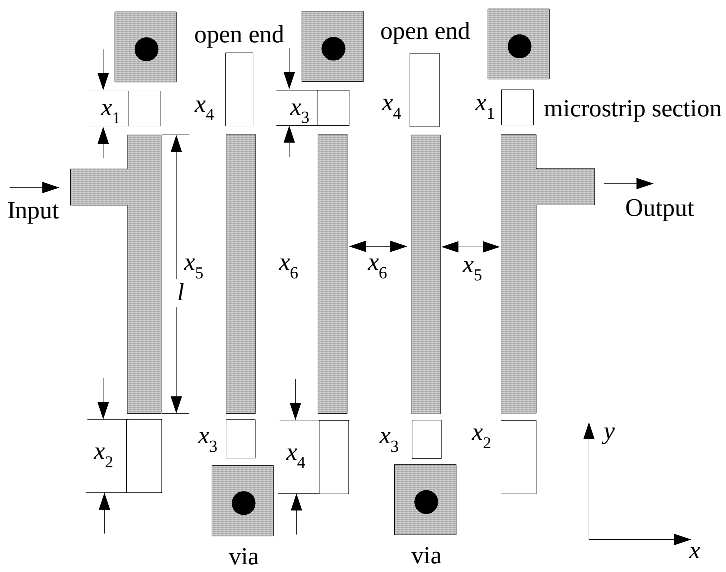
A Five-pole Interdigital Filter Design

(*Bandler et al., 1997*)

Sonnet's ***em*** model



decomposed coarse model

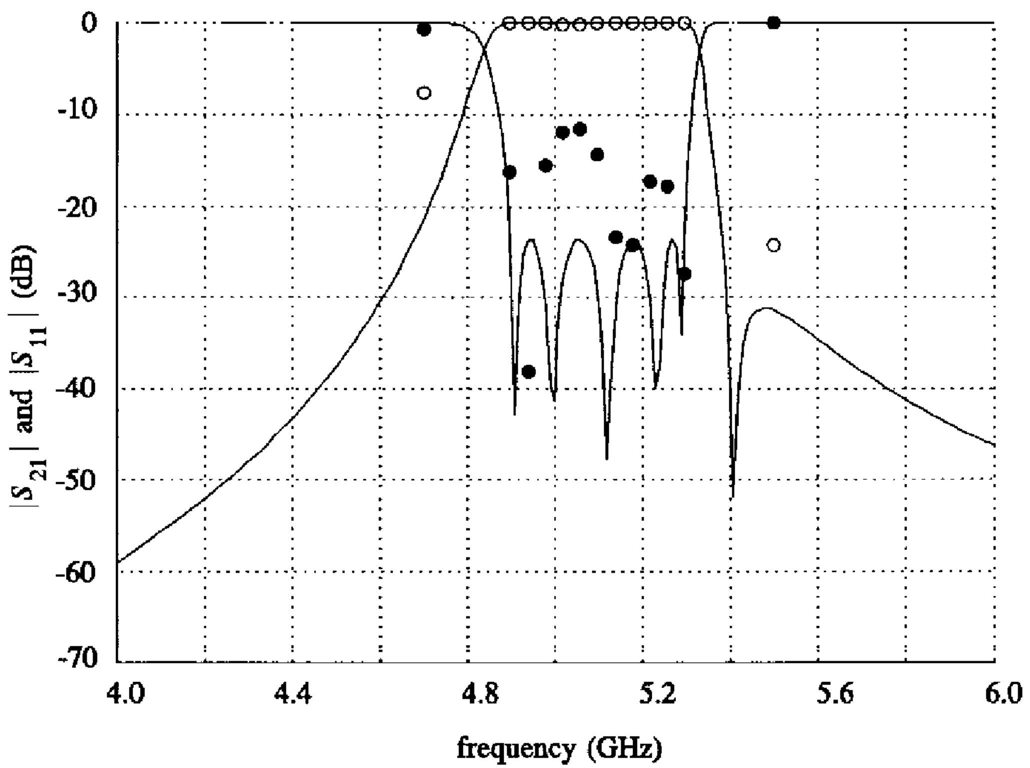


passband ripple ≤ 0.1 dB for 4.9 GHz ≤ ω ≤ 5.3 GHz

isolation: 30 dB, isolation bandwidth: 0.95 GHz

A Five-pole Interdigital Filter Design (continued)

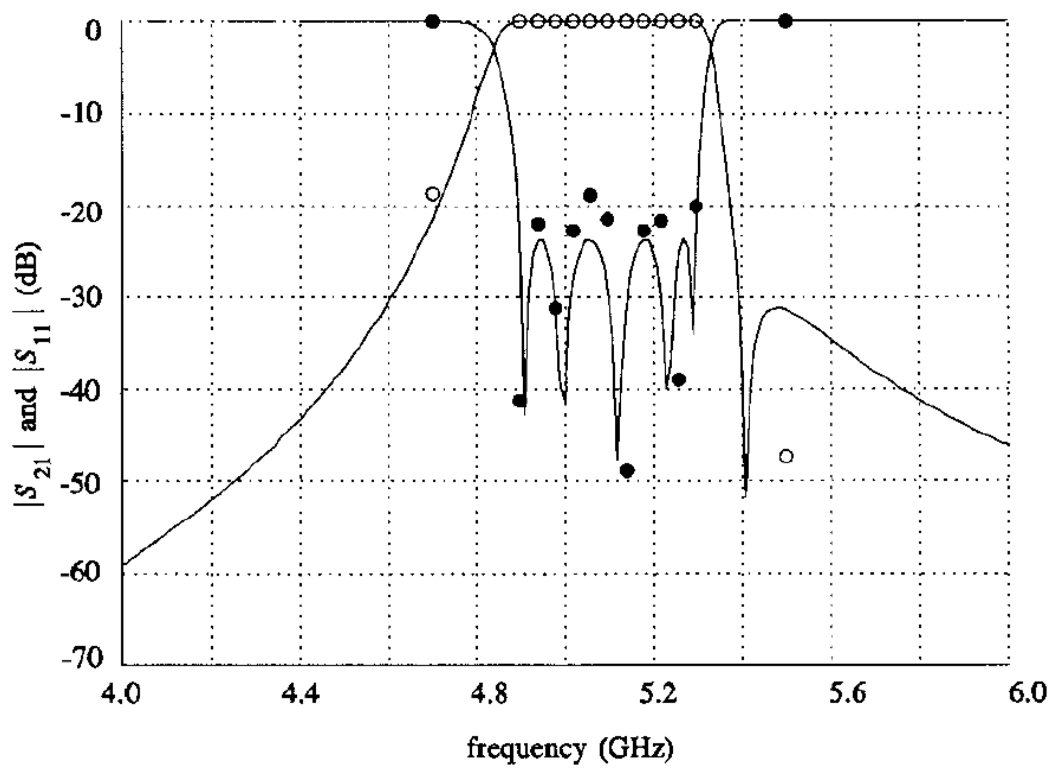
(*Bandler et al., 1997*)



starting point

A Five-pole Interdigital Filter Design (continued)

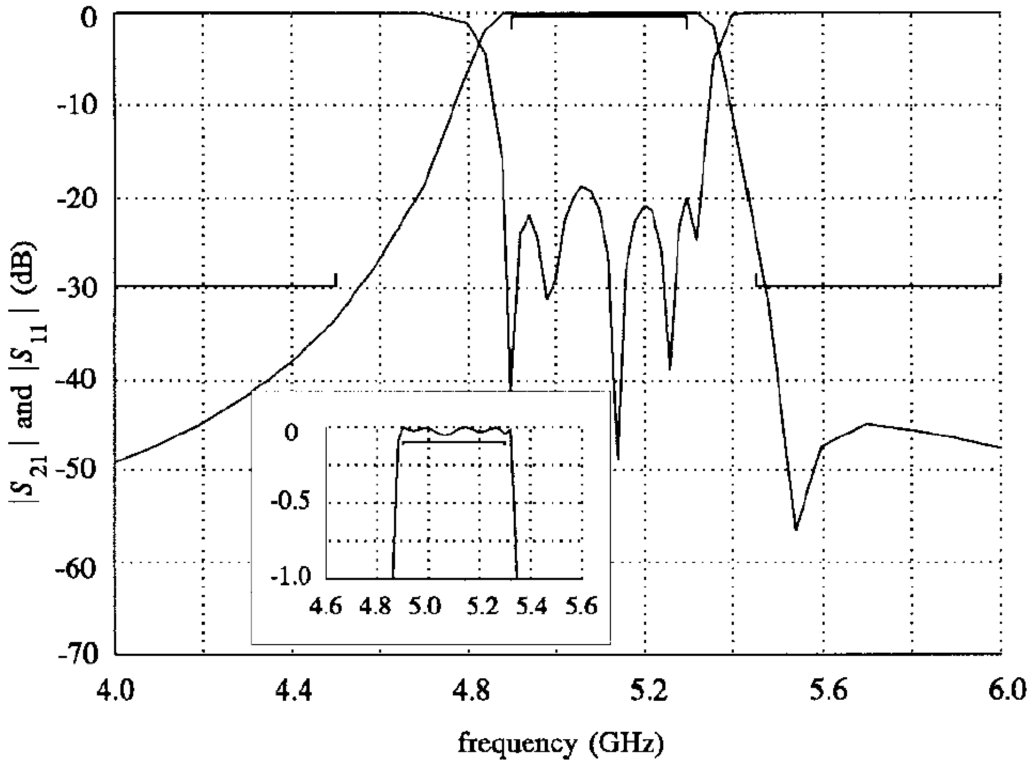
(*Bandler et al., 1997*)



second iteration

A Five-pole Interdigital Filter Design (continued)

(*Bandler et al., 1997*)



second iteration, fine frequency sweep

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Mathematical Motivation for Space Mapping

at the current iterate, a first-order Taylor model

$$L_f(x_f^{(j)} + h) \approx R_f(x_f^{(j)}) + J_f(x_f^{(j)})h$$

the deviation of this model from R_f can be bounded as

$$\left\| R_f(x_f^{(j)} + h) - L_f(x_f^{(j)} + h) \right\| \le C_T \left\| h \right\|^2$$

Taylor approximation to P

$$L_P(x_f^{(j)} + h) \approx P(x_f^{(j)}) + J_P(x_f^{(j)})h$$

the approximation bound

$$\left\| P(x_f^{(j)} + h) - L_P(x_f^{(j)} + h) \right\| \le C_P \left\| h \right\|^2$$

constant

Mathematical Motivation for Space Mapping

the difference between $\boldsymbol{R}_f$ and the mapped coarse model can be bounded as follows

$$\left\| \boldsymbol{R}_f(\boldsymbol{x}_f^{(j)} + \boldsymbol{h}) - \boldsymbol{R}_c(\boldsymbol{P}(\boldsymbol{x}_f^{(j)} + \boldsymbol{h})) \right\|$$

$$\leq \varepsilon + C_P \cdot \left\| \boldsymbol{J}_c(\boldsymbol{P}(\boldsymbol{x}_f^{(j)})) \right\| \cdot \left\| \boldsymbol{h} \right\|^2$$

C_T and C_P are problem specific constants

ε is a constant independent of $\boldsymbol{x}_f$

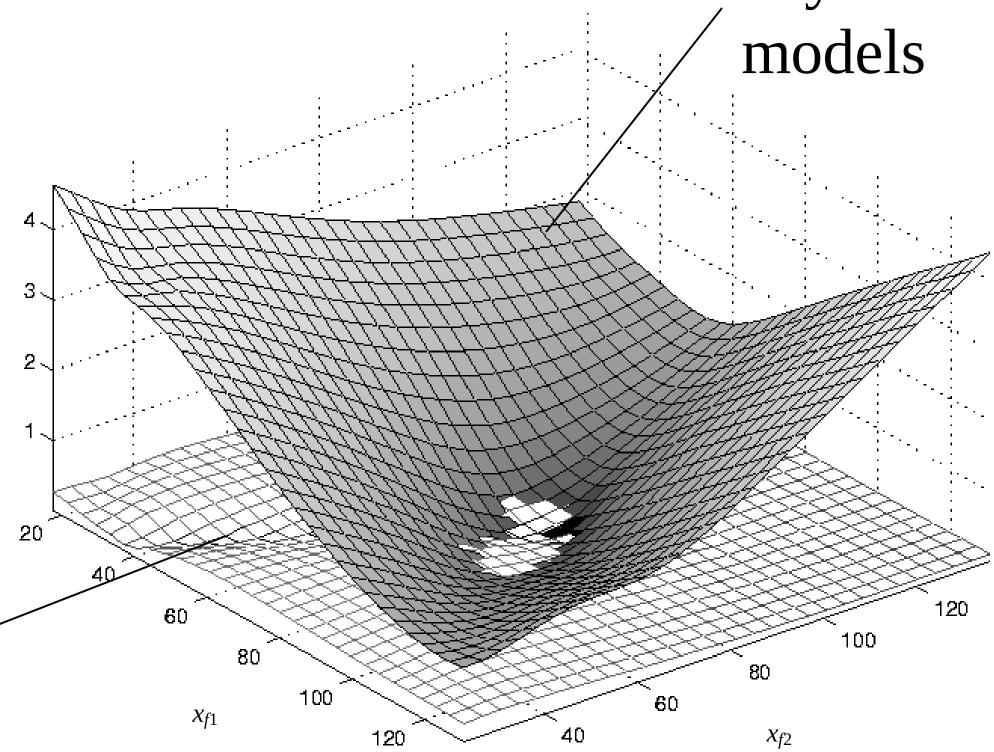
Mathematical Motivation for Space Mapping

the Space Mapped model is a good approximation far from $\boldsymbol{x}_f^*$

the first-order Taylor model is best close to $\boldsymbol{x}_f^*$

error between Taylor and fine models

model effectiveness plot for a two-section capacitively loaded impedance transformer (*Bakr et al. 2001*)



error between Space Mapped and fine models

Trust Regions and Aggressive Space Mapping

solving equivalent problem

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

where $\boldsymbol{B}^{(j)}$ is an approximation to the Jacobian of mapping $\boldsymbol{P}$ and is updated using Broyden's formula

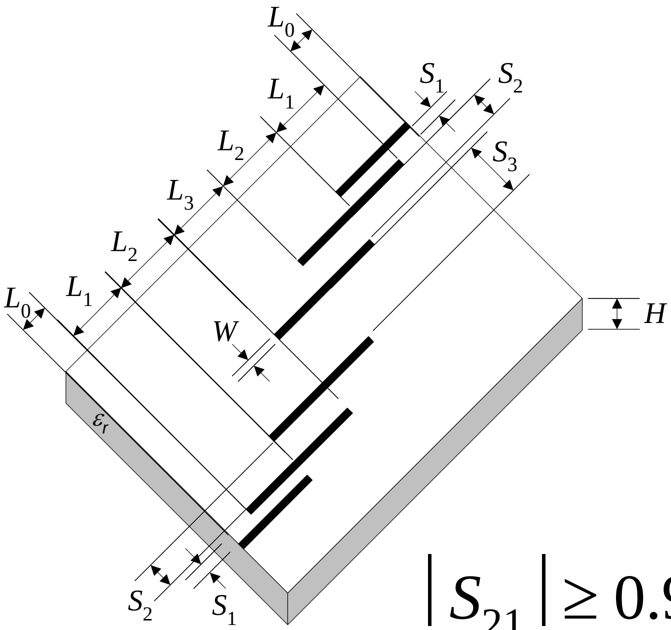
λ and δ (trust region size) are related

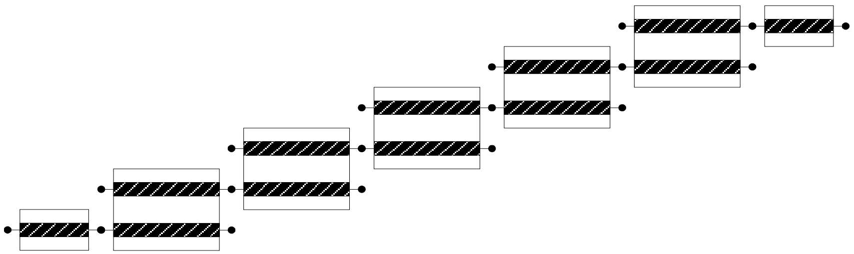
λ is the Lagrange multiplier for the trust region constraint

Trust Regions and Aggressive Space Mapping

(*Bandler et al., 1993-2003*)

HTS quarter-wave parallel coupled-line microstrip filter
(*Westinghouse, 1993*)





$$|S_{21}| \geq 0.95 \ \text{ for } \ 4.008 \text{ GHz} \leq \omega \leq 4.058 \text{ GHz}$$

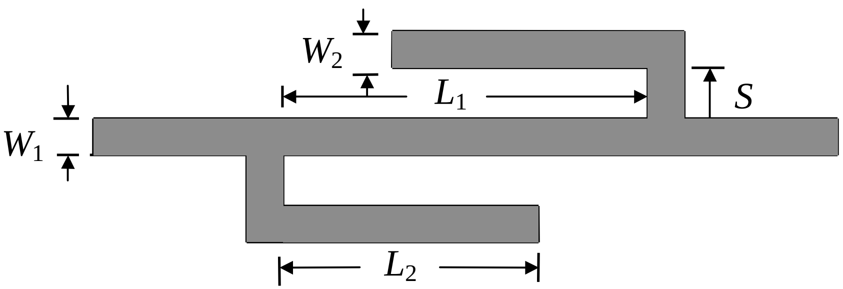
$$|S_{21}| \leq 0.05 \ \text{ for } \ \omega \leq 3.967 \text{ GHz} \ \text{ and } \ \omega \geq 4.099 \text{ GHz}$$

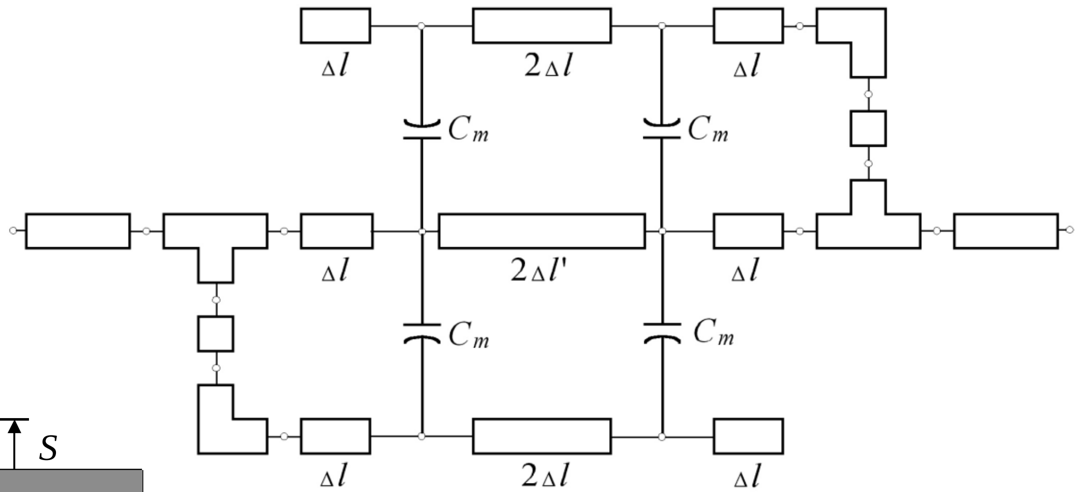
Hybrid Aggressive Space Mapping Optimization

(*Bakr et al., 1999*)

double-folded stub filter

(*Rautio, 1992*)



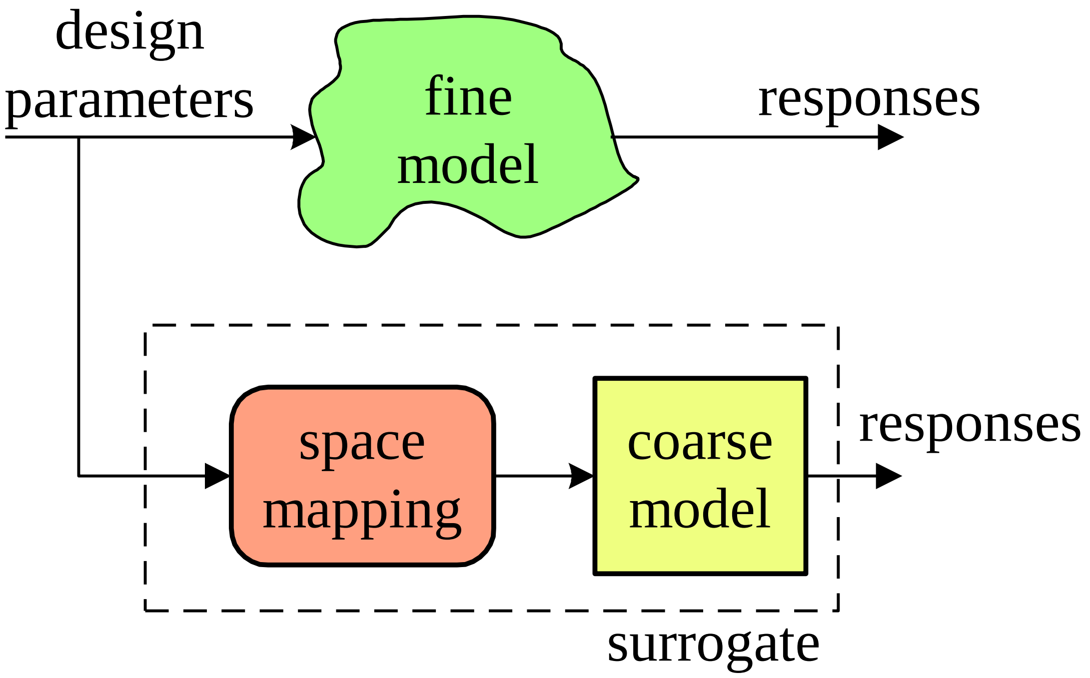


$$|S_{21}| \geq -3 \text{ dB} \quad \text{for} \quad \omega \leq 9.5 \text{ GHz} \quad \text{and } \omega \leq 16.5 \text{ GHz}$$

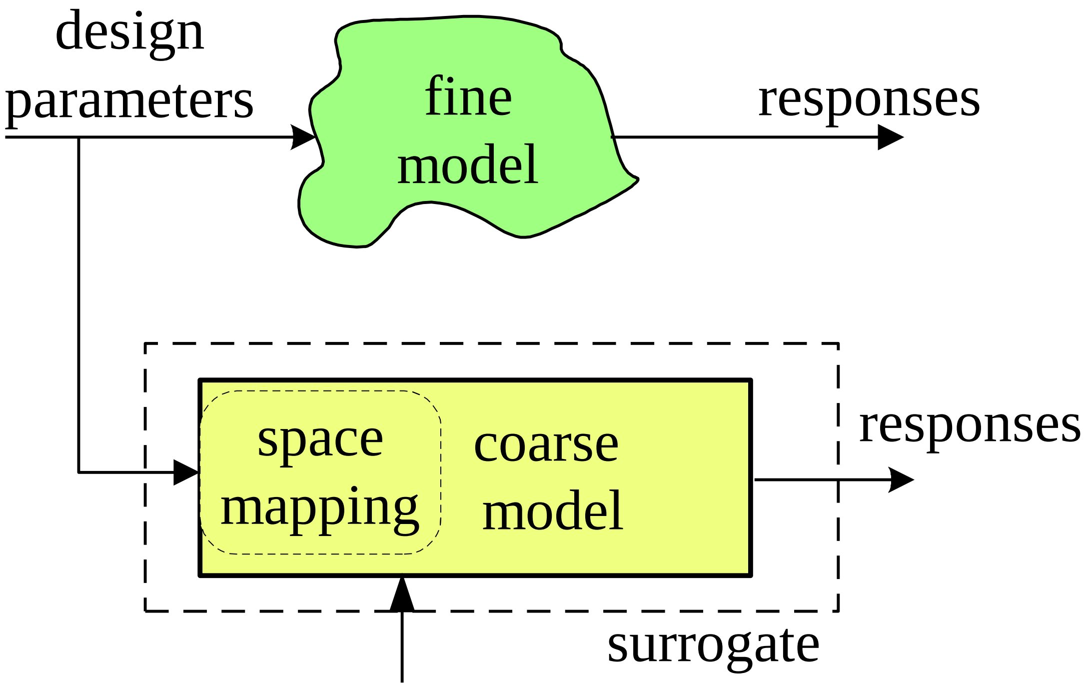
$$|S_{21}| \leq -30 \text{ dB} \quad \text{for} \quad 12 \text{ GHz} \leq \omega \leq 14 \text{ GHz}$$

Explicit Space Mapping Concept

(*Bandler et al., 1994-*)



Implicit Space Mapping Concept
(*Bandler et al., 2004*)



Implicit Space Mapping Practice—Cheese Cutting Problem

(*Bandler, 2002*)

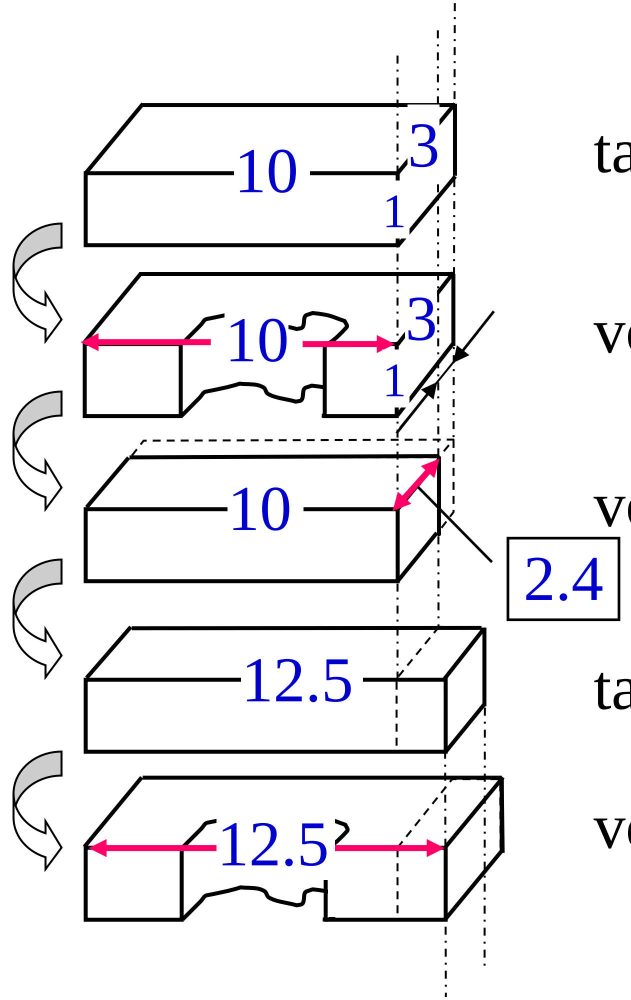
optimal coarse model — target volume =30

initial guess — volume =24

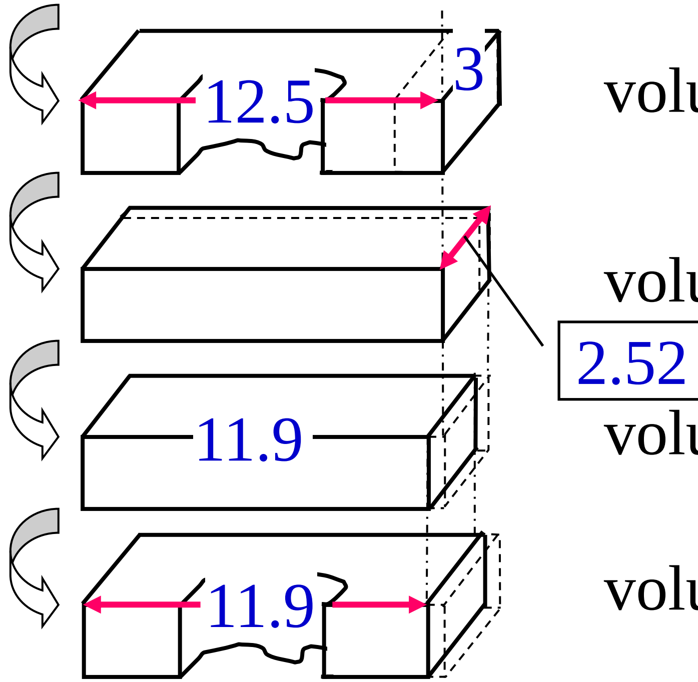
PE — volume =24

prediction — target volume =30

verification — volume =31.5



Implicit Space Mapping Practice—Cheese Cutting Problem
(*Bandler, 2002*)



verification — volume = 31.5

PE — volume = 31.5

prediction — volume = 30.0

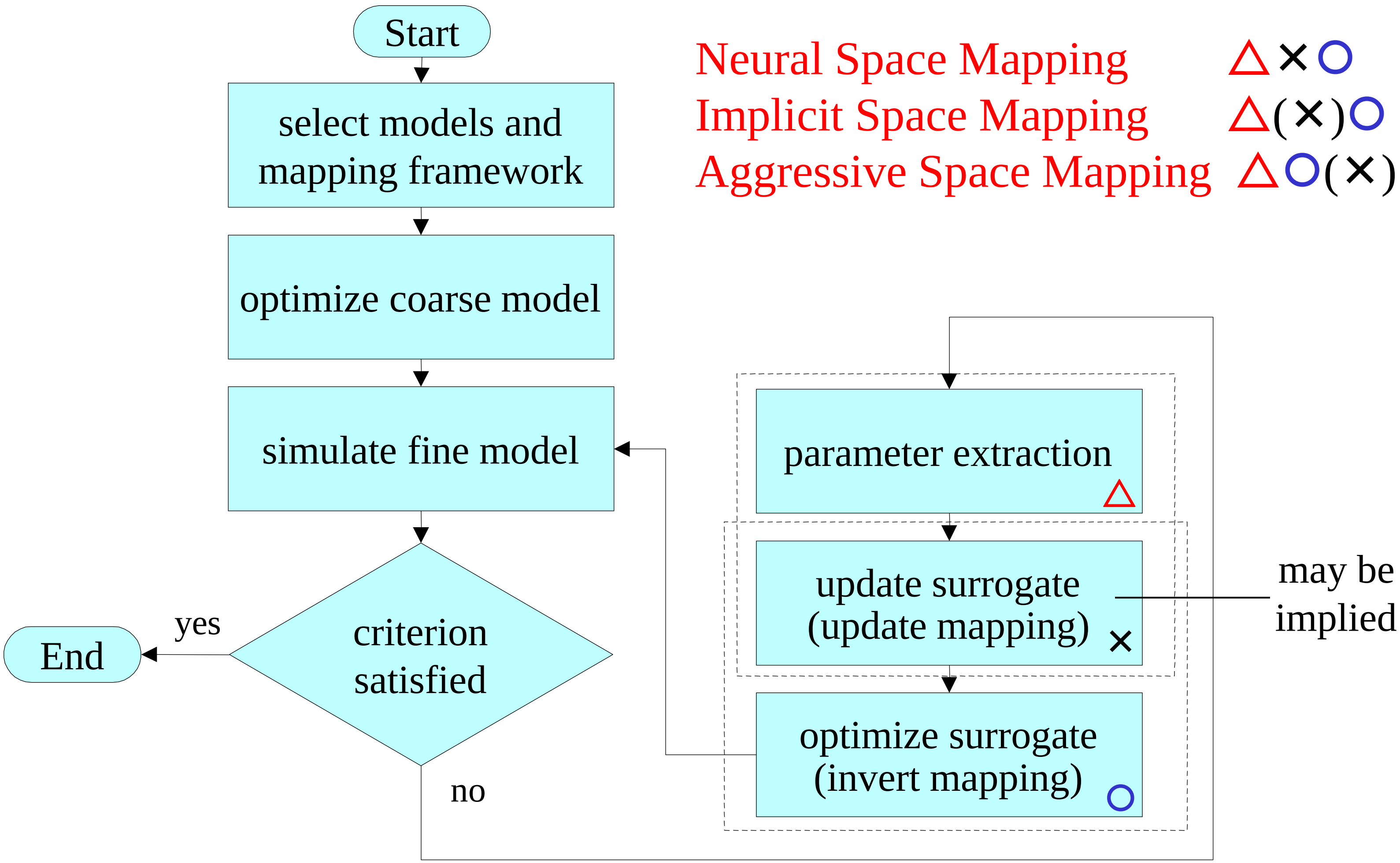
verification — volume = 29.7

⋮

error = (30–29.7)/30×100%
=1%

Space Mapping Framework
(*Bandler et al., 2004*)

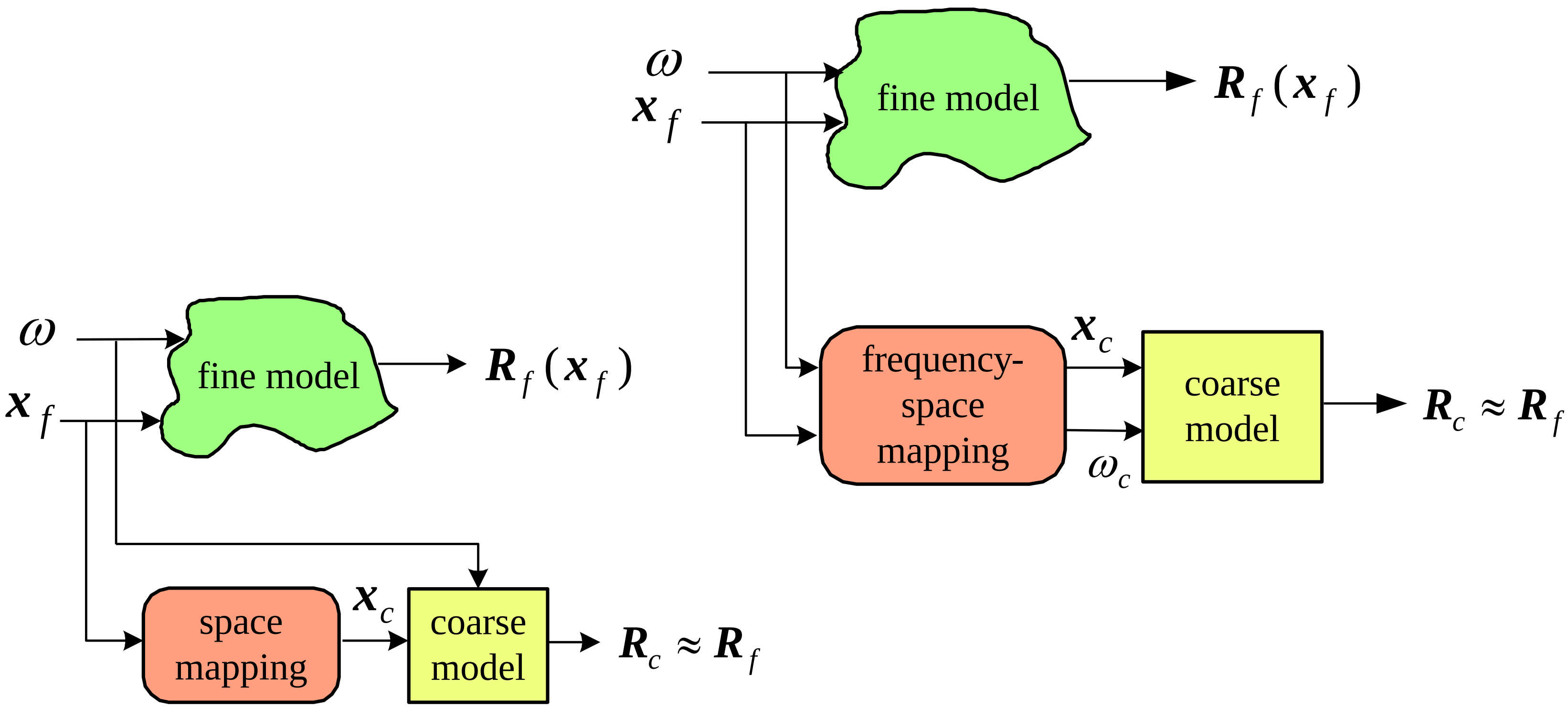
Neural Space Mapping △ × ○
Implicit Space Mapping △ (×) ○
Aggressive Space Mapping △ ○ (×)



Model Enhancement—the SM Tableau Approach

(*Bandler et al., 2001*)

already used in the RF industry for new library models (*Snel*, *2001*)



Space Mapping Implementation and Applications 1

RF and microwave implementation (*Bandler et al., 1994-2003*)

civil engineering structural design (*Leary et al., 2000*)

automobile crashworthiness design (*Redhe et al., 2001-2002*)

generating microwave neural models (*Devabhaktuni et al., 2002*)

combline filter design (*Swanson and Wenzel, 2001*)

microwave filter design (*Harscher, et al., 2002, 2003*)

CAD of integrated passive elements on PCBs (*Draxler, 2002*)

Space Mapping Implementation and Applications 2

CAD technique for microstrip filter design
(*Ye and Mansour, 1997*)

SM models (model enhancement) for RF components (*Snel, 2001*)

multilayer microwave circuits (LTCC) (*Pavio et al., 2002*)

cellular power amplifier output matching circuit (*Lobeek, 2002*)

multilevel ASM strategy applied to filter optimization
(*Safavi-Naeini et al., 2002*)

coupled resonator filter (*Pelz, 2002*)

Space Mapping Implementation and Applications 3

LTCC RF passive circuit design (*Wu et al., 2002*)

waveguide filter design (*Steyn et al., 2001*)

inductively coupled filters (*Soto et al., 2000*)

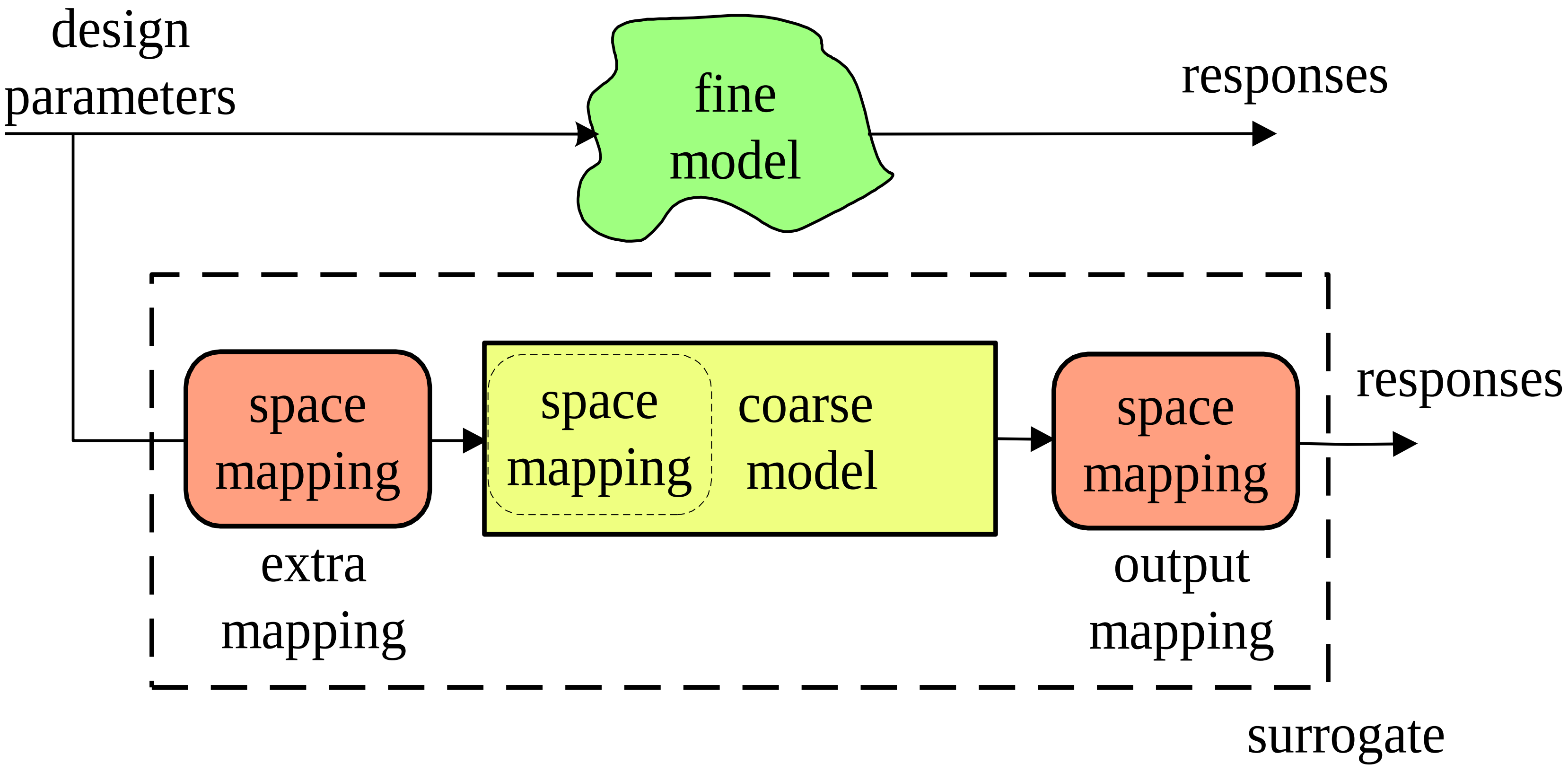
magnetic systems (*Choi et al., 2001*)

Implicit Space Mapping optimization with preassigned parameters (*Bandler et al., 2002*)

Output Space Mapping optimization (*Bandler et al., 2003*)

Implicit, Extra and Output Space Mappings

(*Bandler et al., 2003*)



Space Mapping Implementation and Applications 4

EM-based optimization of microwave oscillators
(*Rizzoli et al., 2003*)

circuit level, neuro-SM modeling of nonlinear devices
(*Zhang et al., 2003*)

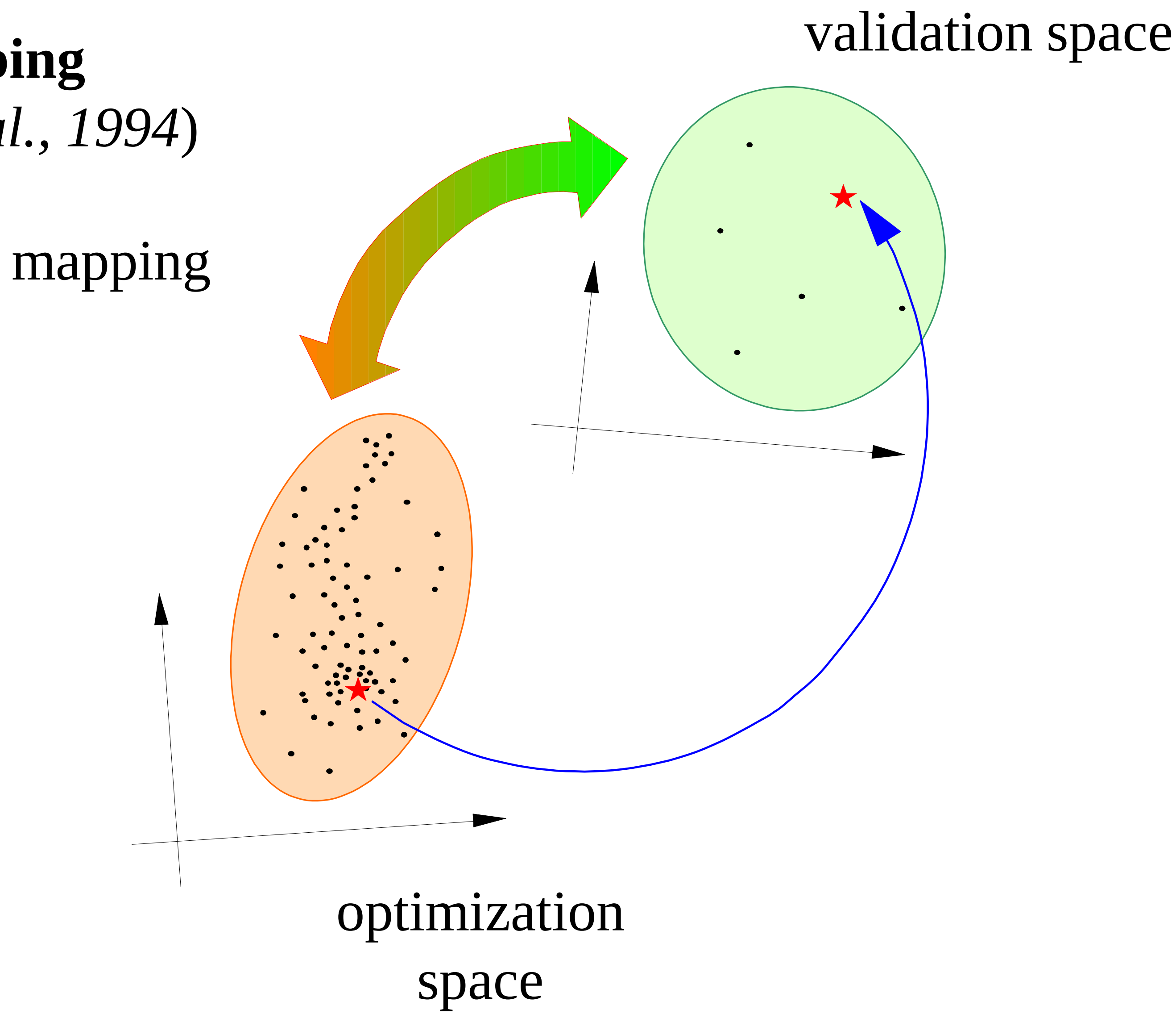
optimization of dielectric resonator filters and multiplexers
(*Ismail et al., 2003*)

waveguide filter design (*Morro et al., 2003*)

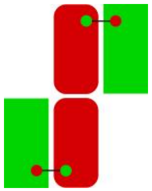
optimal control of partial differential equations
(*Hintermueller and Vicente, 2003*)

Space Mapping

(*Bandler et al., 1994*)



Conclusions



mathematical motivation for Space Mapping

Space Mapping optimization: original (1993)

Aggressive Space Mapping optimization: Broyden-based (1995), trust region, hybrid . . .

parameter extraction

Space Mapping surrogate model based optimization

interesting implementations and applications

References

J.W. Bandler, R.M. Biernacki, S.H. Chen, P.A. Grobelny and R.H. Hemmers, "Space mapping technique for electromagnetic optimization," *IEEE Trans. Microwave Theory Tech.*, vol. 42, 1994, pp. 2536–2544.

J.W. Bandler, R.M. Biernacki, S.H. Chen, R.H. Hemmers and K. Madsen, "Electromagnetic optimization exploiting aggressive space mapping," *IEEE Trans. Microwave Theory Tech.*, vol. 43, 1995, pp. 2874–2882.

J.W. Bandler, R.M. Biernacki, S.H. Chen and Y.F. Huang, "Design optimization of interdigital filters using aggressive space mapping and decomposition," *IEEE Trans. Microwave Theory Tech.*, vol. 45, 1997, pp. 761–769.

M.H. Bakr, J.W. Bandler, K. Madsen and J. Søndergaard, "An introduction to the space mapping technique," *Optimization and Engineering*, vol. 2, 2001, pp. 369–384.

J.W. Bandler, Q.S. Cheng, S.A. Dakroury, A.S. Mohamed, M.H. Bakr, K. Madsen and J. Søndergaard, "Space mapping: the state of the art," *IEEE Trans. Microwave Theory Tech.*, vol. 52, 2004.

References 1

J.W. Bandler, R.M. Biernacki, S.H. Chen, P.A. Grobelny and R.H. Hemmers, "Space mapping technique for electromagnetic optimization," *IEEE Trans. Microwave Theory Tech.*, vol. 42, 1994, pp. 2536–2544.

M.H. Bakr, J.W. Bandler and N. Georgieva, "An aggressive approach to parameter extraction," *IEEE Trans. Microwave Theory Tech.*, vol. 47, 1999, pp. 2428–2439.

J.W. Bandler, R.M. Biernacki, S.H. Chen, R.H. Hemmers and K. Madsen, "Electromagnetic optimization exploiting aggressive space mapping," *IEEE Trans. Microwave Theory Tech.*, vol. 43, 1995, pp. 2874–2882.

J.W. Bandler, R.M. Biernacki, S.H. Chen and Y.F. Huang, "Design optimization of interdigital filters using aggressive space mapping and decomposition," *IEEE Trans. Microwave Theory Tech.*, vol. 45, 1997, pp. 761–769.

J.W. Bandler, R.M. Biernacki and S.H. Chen, "Fully automated space mapping optimization of 3D structures," *IEEE MTT-S IMS Digest*, San Francisco, CA, 1996, pp. 753–756.

J.W. Bandler, R.M. Biernacki, S.H. Chen and D. Omeragic, "Space mapping optimization of waveguide filters using finite element and mode-matching electromagnetic simulators," *Int. J. RF and Microwave Computer-Aided Engineering*, vol. 9, 1999, pp. 54–70.

J.W. Bandler, A.S. Mohamed, M.H. Bakr, K. Madsen and J. Søndergaard, "EM-based optimization exploiting partial space mapping and exact sensitivities," *IEEE Trans. Microwave Theory Tech.*, vol. 50, 2002, pp. 2741–2750.

M.H. Bakr, J.W. Bandler, K. Madsen and J. Søndergaard, "An introduction to the space mapping technique," *Optimization and Engineering*, vol. 2, 2001, pp. 369–384.

M.H. Bakr, J.W. Bandler, R.M. Biernacki, S.H. Chen and K. Madsen, "A trust region aggressive space mapping algorithm for EM optimization," *IEEE Trans. Microwave Theory Tech.*, vol. 46, 1998, pp. 2412–2425.

References 2

J.W. Bandler, R.M. Biernacki, S.H. Chen, W.J. Getsinger, P.A. Grobelny, C. Moskowitz and S.H. Talisa, "Electromagnetic design of high-temperature superconducting microwave filters," *Int. J. Microwave and Millimeter-Wave CAE*, vol. 5, 1995, pp. 331–343.

M.H. Bakr, J.W. Bandler, K. Madsen, J.E. Rayas-Sánchez and J. Søndergaard, "Space mapping optimization of microwave circuits exploiting surrogate models," *IEEE Trans. Microwave Theory Tech*., vol. 48, 2000, pp. 2297–2306.

J.W. Bandler, N. Georgieva, M.A. Ismail, J.E. Rayas-Sánchez and Q. J. Zhang, "A generalized space mapping tableau approach to device modeling," *IEEE Trans. Microwave Theory Tech*., vol. 49, 2001, pp. 67–79.

J.W. Bandler, M.A. Ismail, J.E. Rayas-Sánchez and Q.J. Zhang, "Neuromodeling of microwave circuits exploiting space mapping technology," *IEEE Trans. Microwave Theory Tech.*, vol. 47, 1999, pp. 2417–2427.

M.H. Bakr, J.W. Bandler, M.A. Ismail, J.E. Rayas-Sánchez and Q.J. Zhang, "Neural space-mapping optimization for EM-based design," *IEEE Trans. Microwave Theory Tech*., vol. 48, 2000, pp. 2307–2315.

S.J. Leary, A. Bhaskar and A.J. Keane, "A constraint mapping approach to the structural optimization of an expensive model using surrogates," *Optimization and Engineering*, vol. 2, 2001, pp. 385–398.

M. Redhe, *Simulation Based Design-Structural Optimization at Early Design Stages*, Master Thesis, Dept. of Mechanical Engineering, Division of Solid Mechanics, Linköping University, 581 83 Linköping, Sweden, Thesis. No 922, 2001.

M. Redhe and L. Nilsson, "Using space mapping and surrogate models to optimize vehicle crashworthiness design," 9th AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Atlanta, GA, 2002, AIAA-2002-5536.

J.W. Bandler, Q.S. Cheng, S.A. Dakroury, A.S. Mohamed, M.H. Bakr, K. Madsen and J. Søndergaard, "Space mapping: the state of the art," *IEEE Trans. Microwave Theory Tech.*, vol. 52, 2004.

References 3

V. Devabhaktuni, B. Chattaraj, M.C.E. Yagoub and Q.J. Zhang, "Advanced microwave modeling framework exploiting automatic model generation, neural networks and space mapping," *IEEE MTT-S IMS Digest*, Seattle, WA, 2002, pp. 1097–1100.

D. G. Swanson, Jr., and R. J. Wenzel, "Fast analysis and optimization of combline filters using FEM," *IEEE MTT-S IMS Digest*, Phoenix, AZ, 2001, pp. 1159–1162.

P. Harscher, E. Ofli, R. Vahldieck and S. Amari, "EM-simulator based parameter extraction and optimization technique for microwave and millimeter wave filters," *IEEE MTT-S IMS Digest*, Seattle, WA, 2002, pp. 1113–1116.

P. Draxler, "CAD of integrated passives on printed circuit boards through utilization of multiple material domains," *IEEE MTT-S IMS Digest*, Seattle, WA, 2002, pp. 2097–2100.

S. Ye and R.R. Mansour, "An innovative CAD technique for microstrip filter design," *IEEE Trans. Microwave Theory Tech.*, vol. 45, 1997, pp. 780–786.

J. Snel, "Space mapping models for RF components," Workshop on Statistical Design and Modeling Techniques For Microwave CAD, *IEEE MTT-S IMS*, Phoenix, AZ, 2001.

A.M. Pavio, J. Estes and L. Zhao, "The optimization of complex multi-layer microwave circuits using companion models and space mapping techniques," Workshop on Microwave Component Design Using Space Mapping Methodologies, *IEEE MTT-S IMS*, Seattle, WA, 2002.

J.-W. Lobeek, "Space mapping in the design of cellular PA output matching circuits," Workshop on Microwave Component Design Using Space Mapping Methodologies, *IEEE MTT-S IMS*, Seattle, WA, 2002.

S. Safavi-Naeini, S.K. Chaudhuri, N. Damavandi and A. Borji, "A multi-level design optimization strategy for complex RF/microwave structures," Workshop on Microwave Component Design Using Space Mapping Methodologies, *IEEE MTT-S IMS*, Seattle, WA, 2002.

References 4

D. Pelz, “Coupled resonator filter realization by 3D-EM analysis and space mapping,” Workshop on Microwave Component Design Using Space Mapping Methodologies, *IEEE MTT-S IMS*, Seattle, WA, 2002.

K.-L. Wu, M. Ehlert and C. Barratt, “An explicit knowledge-embedded space mapping scheme for design of LTCC RF passive circuits,” Workshop on Microwave Component Design Using Space Mapping Methodologies, *IEEE MTT-S IMS*, Seattle, WA, 2002.

W. Steyn, R. Lehmensiek and P. Meyer, “Integrated CAD procedure for IRIS design in a multi-mode waveguide environment,” *IEEE MTT-S IMS Digest*, Phoenix, AZ, 2001, pp. 1163–1166.

P. Soto, A. Bergner, J.L. Gomez, V.E. Boria and H. Esteban, “Automated design of inductivity coupled rectangular waveguide filters using space mapping optimization,” *European Congress on Computational Methods in Applied Science And Engineering*, Barcelona, Spain, Sept. 2000.

H.-S. Choi, D.H. Kim, I.H. Park and S.Y. Hahn, “A new design technique of magnetic systems using space mapping algorithm,” *IEEE Trans. Magnetics*, vol. 37, 2001, pp. 3627–3630.

J.E. Dennis, Jr., “A Summary of the Danish Technical University November 2000 Workshop,” Dept. Computational and Applied Mathematics, Rice University, Houston, Texas, 77005-1892, USA.

J.W. Bandler and K. Madsen, “Editorial—surrogate modelling and space mapping for engineering optimization,” *Optimization and Engineering*, vol. 2, 2001, pp. 367–368.

J.E. Dennis, Jr., Dept. Computational and Applied Mathematics, Rice University, Houston, Texas, 77005-1892, USA, private discussions, 2001, 2002.

J.W. Bandler, Q.S. Cheng, D.H. Gebre-Mariam, K. Madsen, F. Pedersen and J. Søndergaard , “EM-based surrogate modeling and design exploiting implicit, frequency and output space mappings ,” *IEEE MTT-S IMS Digest*, Philadelphia, PA, 2003.