PARAMETERIZATION OF ARBITRARY GEOMETRICAL STRUCTURES FOR AUTOMATED ELECTROMAGNETIC OPTIMIZATION

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ABSTRACT

For the first time, this paper reveals and discusses the theoretical foundation of the Geometry Capture™ technique. Geometry Capture facilitates user-parameterization, through graphical means, of arbitrary 2D and 3D geometrical structures. This makes it possible to optimize the shape and dimensions of geometrical objects in an automated electromagnetic design process by adjusting the user-defined parameters subject to explicit numerical bounds and implicit geometrical constraints.

INTRODUCTION

Recent research results [1-4] and the corresponding explosion of available electromagnetic (EM) simulators (e.g., [5-9]) are important factors in the development of a new generation of microwave design tools. Advances in computer hardware make this approach feasible, though still very CPU intensive. The potential and importance of EM-based optimal design have been fully confirmed by recent events [10, 11] and we expect widespread use of this approach in the future. The number of reported applications is already growing rapidly.

Automated EM optimization has raised a number of challenges. Some have been already successfully addressed [12-15] including geometrical interpolation and modeling, reconciling and exploiting the discrete nature of numerical EM solvers with the requirement of continuous variables and gradients by the optimizers, as well as parallel computation combined with efficient data base handling. Techniques, such as Space Mapping™ [16] will play a pivotal role in effective utilization of EM design tools.

This paper addresses the critical issue (see [17]) of parameterization of geometrical structures for the purpose of layout-based design, in particular automated EM optimization. As the optimization process proceeds, revised structures must be automatically generated. Moreover, each such structure must be physically meaningful and should follow the designer's intention w.r.t. allowable modifications and possible limits. It is of utmost importance to leave the parameterization process to the user. In our earlier work (*Empipe Version 1.1, 1992*) we created a library of predefined elements (lines, junctions, bends, gaps, etc.), that were already parameterized and ready for optimization. The applicability of that approach is, however, limited to structures that are decomposable into the available library elements. No library, no matter how comprehensive, will satisfy all microwave designers, simply because of their creativity in devising new structures. Moreover, the library approach inherently omits possible proximity couplings between the elements since they are individually simulated by an EM solver and connected by a circuit-level simulator.

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GEOMETRY CAPTURE

The most significant features of EM simulators include their unsurpassed accuracy, extended validity ranges, and the capability of handling fairly arbitrary geometrical structures. In order to take full advantage of these features the structures may need to be simulated in their entirety. Decomposition into substructures, which might be desired from the point of view of computational efficiency, should be considered only if no significant couplings are neglected. This means that the microwave designer expects to be able to optimize increasingly more complex structures. To provide a tool for parameterizing such structures, we created the user-friendly Geometry Capture™ technique (*Empipe Version 2.0, 1994*), already announced in [18]. Here, for the benefit of the microwave community at large, we examine theoretical and implementational concepts and reveal the mathematical foundation of that technique.

MATHEMATICAL DESCRIPTION OF GEOMETRICAL OBJECT

Every structure to be simulated by an EM solver consists of a number of 2D or 3D objects. Each object must be uniquely defined by its attributes and a finite ordered set of numerical values. The attributes determine the class of objects into which a particular object falls (for example, a polygon or a polytope) as well as how the numerical values are interpreted by the specific EM solver. These numerical values typically represent absolute coordinates of points which form a defining set for the object. For example, a specific polygon can be defined by a sequence of its vertices, with the assumption that each pair of consecutive vertices determines an edge, i.e., they are connected by a line segment (with the last vertex connected to the first one). In contrast, a purely mathematical description of objects such as defining its boundary by a (possibly implicit) function may not be quite practical, could limit available shapes, etc.

It is possible for some of the numerical values defining an object to represent parameters such as the length or width of a rectangle, or the angle or radius of a radial stub. Such

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parameters are of direct interest to the designer. If all numerical values represented such parameters and if they were readily available then there would be no need for parameterization. However, some of the values (if not all) must represent absolute geometrical coordinates for the simple reason of indicating relative placement of an individual object w.r.t. to all other objects, as well as to facilitate handling of fairly arbitrary structures. Therefore, in the following discussion we concentrate on those absolute coordinates only, assuming for simplicity that they represent vertices.

Consider an ordered set of vertices of an object as described by

$$x_{v1},\ x_{v2},\ \ldots,\ x_{vm} \tag{1}$$

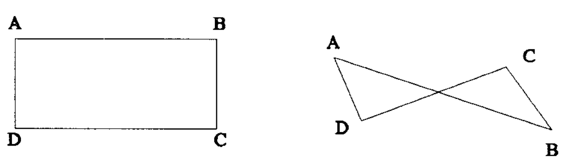
where m is the total number of vertices and each x_{vi} is the vector of the vertex coordinates. Depending on the object it is either a two- or three-dimensional vector. All the vertices can be conveniently represented by a single vector

$$x = [\ x_{v1}^T\ \ x_{v2}^T \ldots\ x_{vm}^T\ ]^T \tag{2}$$

which combines all the coordinates in an ordered manner. The space of all vectors x will be denoted by X (it can be either R^{2m} or R^{3m}).

IMPLICITLY CONSTRAINED COORDINATE SYSTEM

Considering x in (1) as a vector of unconstrained optimization variables can easily lead to unacceptable results. This is illustrated by Fig. 1. Starting from the object shown in Fig. 1(a) it is possible for the optimizer to suggest the values leading to the situation depicted in Fig. 1(b). This may pose serious difficulties - the best an EM solver can do is to employ a sophisticated rule checker and to dismiss the suggested values. Such a rule checker will not be normally available to the optimizer.



(a) (b)

Fig. 1. Arbitrary movement of vertices of a polygon: (a) the initial geometry, and (b) an unwanted result due to an arbitrary and independent movement of vertices.

In order to impose constraints on the movement of the vertices we consider a function T mapping certain designable or optimizable parameters ϕ into X as

$$x = T(\phi) \tag{3}$$

and assume that the parameters are allowed to vary within an orthotope specified by

$$\phi_{i\,\min} \le \phi_i \le \phi_{i\,\max},\quad i = 1, 2, \ldots, n \tag{4}$$

There will normally be very few parameters ϕ as compared with the number of vertices ($n \ll m$). The process of parameterizing an object consists of selecting the parameters ϕ, defining and determining the function T, and establishing the constraints (4). Finally, discretization of the parameters ϕ needs to be considered.

DEFINING CONTROLLING PARAMETERS AND OBJECT EVOLUTION

As already mentioned, defining the parameters ϕ should be left to the designer who knows best what changes to the object are desired and allowable. This process is actually quite intuitive. A few rules, however, should be followed. First, there should be as few parameters as possible. Secondly, the parameters must not be inconsistent, or dependent. This means that, if independently changed, they must not contradict each other. For example, attempting to define all partial lengths as well as the total length is incorrect. A clear understanding of how the object evolves when a parameter is varied, as well as of the limits to be specified by (4) is crucial. This is particularly important in preserving the physical meaning of the object. Finally, a basic understanding of the mapping (3), as discussed in the next section, is needed. *It is worth emphasizing that the parameter values, as seen by the optimizer, are intermediate to the process of generating actual layouts.* Therefore, parameter transformations such as scaling or normalization can be used to link those optimizable parameters with the actual layout design parameters.

Object evolution and defining the parameters is illustrated by Fig. 2.

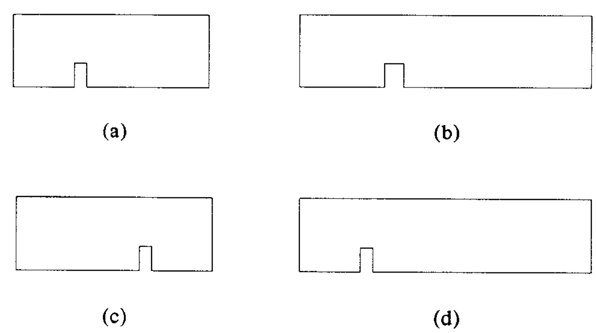


Fig. 2. Various evolutions of a microstrip line with a slit: (a) the initial geometry, (b) proportional expansion of the whole structure along the x axis, (c) only the location of the slit in the fixed line is allowed to change, and (d) only the segment to the right of the slit is allowed to expand.

Assuming that the location of the left edge is fixed the evolution of the object can be described by only one parameter in all cases. However, its definition, and more importantly its impact on the location of the vertices, will be different. Normally, one would select the overall length, the distance between the slit and the left edge, or the distance between the slit and the right edge in the case of Fig. 2(b), (c), or (d), respectively. The importance of the limits (4) is particularly evident in the case of Fig. 2(c). Another example is shown in Fig. 3 where one parameter controls the length of the right edge in a symmetric manner.

(a) (b)

Fig. 3. Evolution of a rectangle (a) to a tapered line (b).

DEFINING THE MAPPING

The mapping (3) will be defined w.r.t. to the starting, or nominal, object $\boldsymbol{x}^0$

$$\boldsymbol{x}^0 = \boldsymbol{T}(\boldsymbol{\phi}^0) \tag{5}$$

where $\boldsymbol{\phi}^0$ represents the nominal values of the parameters $\boldsymbol{\phi}$. In other words, we consider the following form of $\boldsymbol{T}$

$$\boldsymbol{T}(\boldsymbol{\phi}) = \boldsymbol{T}(\boldsymbol{\phi}^0) + \boldsymbol{F}(\boldsymbol{\phi}-\boldsymbol{\phi}^0) \tag{6}$$

As long as the vectors $\boldsymbol{x}^0$ and $\boldsymbol{\phi}^0$ are known (specified by the designer), only the function $\boldsymbol{F}$ in (6) needs to be identified. The movement of individual vertices w.r.t. the nominal object is then

$$\boldsymbol{x}_{vi} = \boldsymbol{x}_{vi}^0 + \boldsymbol{f}_i(\boldsymbol{\phi}-\boldsymbol{\phi}^0) \tag{7}$$

where $\boldsymbol{f}_i$, $i = 1, 2, ..., m$, are the subvectors of $\boldsymbol{F}$ such that

$$\boldsymbol{F} = [\, \boldsymbol{f}_1^T \;\; \boldsymbol{f}_2^T \ldots \boldsymbol{f}_m^T \,]^T \tag{8}$$

A principal assumption we make about the mapping is that the functions $\boldsymbol{f}_i^T$ are additive w.r.t. the contributions due to incremental changes in individual parameters. This is expressed mathematically as

$$\boldsymbol{f}_i(\boldsymbol{\phi}-\boldsymbol{\phi}^0) = \sum \boldsymbol{f}_{ij}(\phi_j-\phi_j^0) \tag{9}$$

and, in the case of two parameters, is illustrated in Fig. 4.

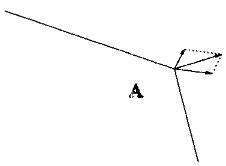


Fig. 4. Additiveness of the vertex movement w.r.t. the changes in individual parameters.

Under this assumption, defining the mapping (3) can be carried out by identifying the functions $\boldsymbol{f}_{ij}$ in (9). Each such function determines the trajectory of the movement of a specific vertex due to a change in one parameter alone. An example of such a trajectory is shown in Fig. 5. An important consequence of (9) is that $\boldsymbol{F}$ in (6) can be expressed as

$$\boldsymbol{F}(\boldsymbol{\phi}-\boldsymbol{\phi}^0) = \sum \boldsymbol{F}_j(\phi_j-\phi_j^0) \tag{10}$$

where each term on the RHS indicates the evolution of the whole object due to a change in one parameter alone. This means that the process can be split into steps in which the user characterizes the evolution of the whole structure in response to changes in one parameter at a time.

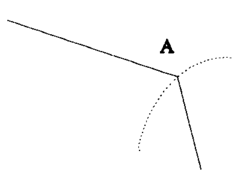


Fig. 5. Possible trajectory of the movement of a vertex with a change in a parameter.

DISCRETIZATION OF CONTROLLING PARAMETERS

The problem of parameter discretization may arise out of necessity if the particular EM simulator used is a fixed grid solver. If this is the case, all the (user-defined) parameters must be discretized in such a manner that for on-grid parameter values the mapped vertices are also on the grid. Although not trivial theoretically, this can be assured in an intuitive way using a graphical editor.

Even if parameter discretization is not enforced by the EM simulator, it might still be desirable to facilitate it in order to take advantage of existing techniques that allow significant improvement of efficiency. These techniques include the utilization of a data base of already simulated structures in conjunction with efficient interpolation and modeling [14]. The benefits of these techniques include efficient gradient evaluation, handling of tolerances, efficient model evaluation in Monte Carlo analysis and yield-driven design.

EXAMPLE

Consider the double folded stub microstrip filter (see for example [14]) shown in Fig. 6.

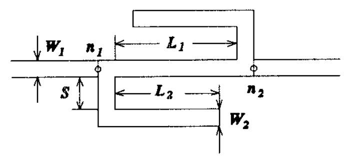


Fig. 6. Double folded stub filter.

We consider changing the overall length of the filter, the length of the folded segments of the stubs, the spacing of the folded segments of the stubs, and the width of the main line and of the stubs as allowable modifications to the structure. This can be controlled by the parameters L_1, L_2, S, W_1 and W_2 marked in the diagram. Here, the parameterization process is implemented by Empipe [19] and ***xgeom*** [5]. First, a nominal structure is fully characterized using ***xgeom***, as shown in Fig. 7.

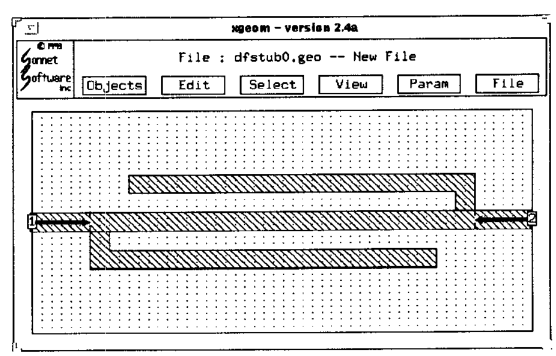
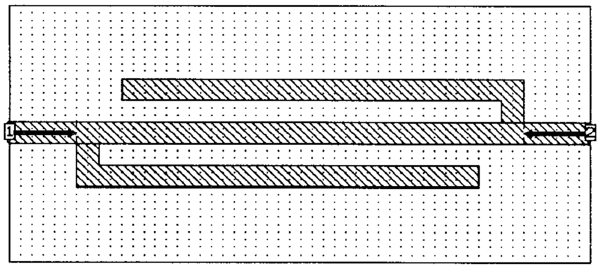
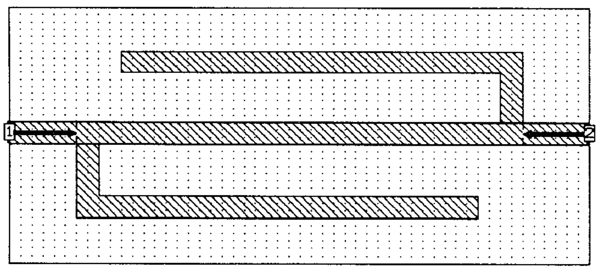


Fig. 7. Parameterization of the double folded stub filter: the nominal geometry.

This includes drawing, specifying the grid, box, substrate, etc., and entering all material constants. Then, the structure is sequentially edited to reflect changes w.r.t. to each optimizable parameter. Every such modified structure needs to be fully characterized. Fig. 8 shows the structures corresponding to S=4.8 mil and to S=11.2 mil, respectively.



(a)



(b)

Fig. 8. Parameterization of the double folded stub filter: (a) the filter structure for S=4.8 mil, and (b) the filter structure for S=11.2 mil.

Similar structures reflecting modifications due to the remaining parameters need to be drawn. Then Empipe's Geometry Capture tool captures the absolute coordinates of all the vertices for the nominal and modified structures. Finally, Empipe prompts the user to provide the values of parameters (4.8 mil and 11.2 mil in the case of Figs. 8(a) and 8(b)) corresponding to all drawings, as well as certain data needed for discretization. As a result, after performing all mathematical calculations, Empipe generates a new optimization-ready library element that can be stored and reused.

CONCLUSIONS

We have examined theoretical concepts and formulations relevant to parameterization of arbitrary geometrical structures for automated layout-based optimization using EM tools. This is to facilitate friendly user-parameterization of user-defined geometrical objects. Once a structure has been parameterized with user-defined parameters controlling its dimensions (size as well as shape), it becomes available for automated optimization. Significantly, the structure can then be saved and reused, thus augmenting a customized library of elements.

Our theoretical derivations are not linked to any particular EM solver. Certain assumptions have been made to keep the technique simple and manageable. We expect that our innovations will become widely used in optimization-oriented layout-based applications, not only in microwave hybrid and monolithic IC design, and not only in conjunction with EM simulators.

REFERENCES

[1] J.C. Rautio and R.F. Harrington, "An electromagnetic time-harmonic analysis of arbitrary microstrip circuits," *IEEE Trans. Microwave Theory Tech.*, vol. 35, 1987, pp. 726-730.

[2] R.H. Jansen and P. Pogatzki, "A hierarchically structured, comprehensive CAD system for field theory-based linear and nonlinear MIC/MMIC design," *1992 2nd Int. Workshop of the German IEEE MTT/AP Joint Chapter on Integrated Nonlinear Microwave and Millimeterwave Circuits Dig.* (Duisburg, Germany), 1992, pp. 333-341.

[3] W.J.R. Hoefer, "Time domain electromagnetic simulation for microwave CAD applications," *IEEE Trans. Microwave Theory Tech.*, vol. 40, 1992, pp. 1517-1527.

[4] V.J. Brankovic, D.V. Krupezevic and F. Arndt, "Efficient full-wave 3D and 2D waveguide eigenvalue analysis by using the direct FD-TD wave equation formulation," *IEEE MTT-S Int. Microwave Symp. Dig.* (Atlanta, GA), 1993, pp. 897-900.

[5] ***em***™ and ***xgeom***™, Sonnet Software, Inc., 135 Old Cove Road, Suite 203, Liverpool, NY 13090-3774, 1995.

[6] *IE3D*™, Zeland Software, Inc., 39120 Argonaut Way, Suite 499, Fremont, CA 94538.

[7] *LINMIC+/N Version 3.0*, Jansen Microwave, Bürohaus am See, Am Brüll 17, D-4030 Ratingen 1, Germany.

[8] *MSC/EMAS*, The MacNeal-Schwendler Corp., 815 Colorado Blvd., Los Angeles, CA 90041-1777.

[9] *HFSS* and *Momentum*, Hewlett-Packard Co., 1400 Fountaingrove Parkway, Santa Rosa, CA 95403.

[10] F. Arndt, J.W. Bandler, W.J.R. Hoefer, A.M. Pavio, J.C. Rautio, R. Sorrentino, D.G. Swanson, Jr., S.H. Talisa, R.J. Trew, "Circuit Design with Direct Optimization-driven Electromagnetic Simulators," Panel Session, IEEE MTT-S Int. Microwave Symp. (San Diego, CA), 1994.

[11] F. Arndt, S.H. Chen, W.J.R. Hoefer, N. Jain, R.H. Jansen, A.M. Pavio, R.A. Pucel, R. Sorrentino and D.G. Swanson, Jr., *Automated Circuit Design using Electromagnetic Simulators.* Workshop WMFE (J.W. Bandler and R. Sorrentino, Organizers and Chairmen), IEEE MTT-S Int. Microwave Symp. (Orlando, FL), 1995.

[12] J.W. Bandler, R.M. Biernacki, S.H. Chen, P.A. Grobelny and S. Ye, "Yield-driven electromagnetic optimization via multilevel multidimensional models," *IEEE Trans. Microwave Theory Tech.*, vol. 41, 1993, pp. 2269-2278.

[13] P.P.M. So, W.J.R. Hoefer, J.W. Bandler, R.M. Biernacki and S.H. Chen, "Hybrid frequency/time domain field theory based CAD of microwave circuits," *Proc. 23rd European Microwave Conf.* (Madrid, Spain), 1993, pp. 218-219.

[14] J.W. Bandler, R.M. Biernacki, S.H. Chen, D.G. Swanson, Jr., and S. Ye, "Microstrip filter design using direct EM field simulation," *IEEE Trans. Microwave Theory Tech.*, vol. 42, 1994, pp. 1353-1359.

[15] F. Alessandri, M. Dionigi, R. Sorrentino and M. Mongiardo, "A fullwave CAD tool of waveguide components using a high speed direct optimizer," *IEEE MTT-S Int. Microwave Symp. Dig.* (San Diego, CA), 1994, pp. 1539-1542.

[16] J.W. Bandler, R.M. Biernacki, S.H. Chen, R.H. Hemmers and K. Madsen, "Aggressive space mapping for electromagnetic design," *IEEE MTT-S Int. Microwave Symp. Dig.* (Orlando, FL), 1995, pp. 1455-1458.

[17] M.A. Schamberger and A.K. Sharma, "A generalized electromagnetic optimization procedure for the design of complex interacting structures in hybrid and monolithic microwave integrated circuits," *IEEE MTT-S Int. Microwave Symp. Dig.* (Orlando, FL), 1995, pp. 1191-1194.

[18] J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen and P.A. Grobelny, "Integrated harmonic balance and electromagnetic optimization with Geometry Capture," *IEEE MTT-S Int. Microwave Symp. Dig.* (Orlando, FL), 1995, pp. 793-796.

[19] *Empipe*™, Optimization Systems Associates Inc., P.O. Box 8083, Dundas, Ontario, Canada L9H 5E7.