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Human- vs Machine Design of Antennas: Observation of bi-phasic behavior in Genetic Shape optimization

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***Abstract*—Random-based global optimization algorithms have been widely used for antenna shape design, primarily in situations where a human-knowledge based solution is not available. In this contribution we study the behavior of a Random-based global optimization in situations where the design can be addressed with a standard human-based design approach and human-driven parameter tweaking via simulations. The present case study involves shape optimization of a 2D pixelated domain, performed via binary coding and a Genetic Algorithm (GA). The reference geometry is a square resonant patch-type antenna with optimized probe feeding position. The initial domain is a pin-centered rectangle larger than the reference patch, so that the optimizer is eventually free to indirectly find the best pin position corresponding to the best design of the patch. A remarkable result is that the GA has a ”bi-phasic” behavior with a jump in the convergence. In an initial ”liquid” phase the geometry occupies the entire larger domain and remains dendritic, with performance inferior to human design; then a jump happens, reminiscent of a phase transition; there, the GA ”condenses” the antenna surface into the smaller region occupied by the resonant square patch, and proceeds to improve the performances beyond those of human design.**

***Index Terms*—Article submission, IEEE, IEEEtran, journal, LaTeX, paper, template, typesetting.**

I. INTRODUCTION

AUTOMATED antenna design encompasses many different instances and approaches, that vary from the very structured array synthesis down to common practitioner ”parameter sweep” offered in commercial simulation suites. It can be always understood as an optimization problems, and sometimes it is convenient to phrase and implement it as such. The more the design instance is comprehensive, and the more it is algorithmic hard. Here we consider the full design of the antenna metal layout, that is, a shape optimization, with examples as in (e.g.) [1], [2]. This problem, like many other of practical relevance, is non-convex and non-linear. This implies the need to use, in general, global optimization algorithms, that are all random-based (like, e.g. the Genetic Algorithm, GA). A crucial problem is the attainment of the global optimum, so that one knows that if the algorithm does not converge the specifications are too tight and need to be relaxed. In general, there is no theoretical prove thereof.

A simpler, yet relevant, simplification would be having some proof that one gets a result that can be trusted.

Interestingly, random-based global optimization is typically applied to design situations where one is unable to provide a simplified model of the problem that leads to design formulas, and/or to few free parameters that are tuned via exhaustive search and simulation (”parameter sweep”). This of course is very logical.

The purpose of this contribution is different: we will address a design problem for which a ”human knowledge” exist and that is routinely performed with the help of (parametric) simulations. The same design instance will be addressed as a ”machine” design, i.e. a full shape optimization via a random-based global algorithm, the GA.

This will allow to make observations on the machine design, and hopefully giving indication for further use.

II. STUDY CASE

We consider the shape optimization of a 2D patch antenna, in air and probe-fed. Design of the common shapes are in most textbooks, and one usually ends the design by an exhaustive search for the probe position; this is what has been done with the results in Fig. 1 and Tab. I; the square patch has been chosen as reference solution. The serrated edges have no other meaning that allowing a higher degree of comparison with the machine design, described below.

The design has been done either at single and multi-frequency to enhance the difference in the behaviour of the optimization process increasing the computational complexity of the fitness function.

III. MACHINE DESIGN

For the ”machine” design we employ the GA-based algorithm coupled with a Method of Moments (MoM) solver for which the (tested) implementation is described in [1], [2]. The surface of the patch is pixelated and metal pixels retained or left void, with a binary coding well suited for the GA. This approach allows to assemble the impedance matrix Z only once at the beginning of the optimization process and then remove time by time only the rows and columns correspondent to the pixels left void i.e. the zeros of the chromosomes arrays. Pixels are hexagonal as in [2] to ensure the connectivity of the optimized structure only across the edges, avoiding ambiguous fabrication due to elements touching only through vertexes, such in the case of quadrangular pixels. The patch surface lies at a height $h = \lambda/15$ from a ground plane modeled as infinite; feeding is via a probe, simplified as a vertical 2D strip of width $d_y = \lambda/50$; excitation is modeled as a voltage gap. The optimization domain is a rectangle of size

$L_x \times L_y = 0.85\lambda \times 0.55\lambda$, indicated as an overlay in Fig. 1; it has been chosen so that the probe feeding position, initially in the center, can be indirectly optimized while optimizing the metal distribution and can result in a range corresponding to that used in human design without having to move the pin junction. In this way the optimizer converges both towards the best structure and the best relative probe positioning at the same time.

In this resonant type of antennas, sidelobes are not typically an issue; hence as performance indicators we initially consider: the gain at broadside, G; the input reflection coefficient Γ_{in} with respect to 50Ω, accounted via the realized gain

$$G_R = (1 - |\Gamma_{in}|^2) G \tag{1}$$

The objective (fitness) function to be maximized then follows directly as the realized gain; an example of the ensuing machine designed structure is in Fig. 2, with the gain reported in Tab. I. As it can be noticed, the gain does increase, but a larger area is occupied, with a typical tendency to form dendritic conductor shapes: this is opposite to the ”human” design approach.

We have tried to force the machine design to produce more ”compact” shapes; this has been done using the graph theory to include a term for the control of the geometry in the fitness function: the rank of the Laplacian matrix associated to the dual mesh is an indicator of the connectivity of the structure [3] and the Euler characteristic can be used to control the number of holes inside the radiating domain.

$$K = V - \mathrm{Rank}(L), \quad H = E - V - F - 1 \tag{2}$$

where K is the number of disconnected sub-graphs and H, V, E and F are respectively the number of holes, vertexes, edges and faces. These term however increments the stiffness, without overall improvement of the performance indicators and without an impact on the convergence towards a ”human-designed” patch.

Hence, aperture efficiency emerged as the natural quality indicator and candidate objective function. We used the ”total” effective area defined with respect to realized gain, and the *occupied area* A_{geom}, defined as the rectangle inscribing the overall metalization; this results in the ”total” aperture effectiveness

$$A_{eff}^{tot} = \frac{\lambda^2}{4\pi} G_R, \quad \nu^{tot} = \frac{A_{eff}^{tot}}{A_{geom}} \tag{3}$$

Then we have optimized this total aperture efficiency without geometrical constraints, with the results in Fig. 6 and Tab. I.

IV. CONCLUSION

These results, while not considerable as fully general, tend to indicate a non optimality of the specific approach for an antenna of resonant size, and the very different nature of the human and machine approaches. This result however should not be taken as an indication of ineffectiveness of the machine design or the specific implementation; for example, in the (significantly) larger case of [2] aperture efficiencies of the order of 60% is comparable to reflectors, and thus a remarkable result.

TABLE I
SUMMARY OF PERFORMANCE RESULTS

	G_R [dB]	$S11$ [dB]	ν^{tot}
Square patch	6.4	-34.3	0.80
G_R only	8.1	-20.6	0.58
G_R + Connectivity	7.9	-16.1	0.55
ν^{tot} only	8.0	-17.0	0.56
ν^{tot} + Connectivity	6.9	-26.7	0.43

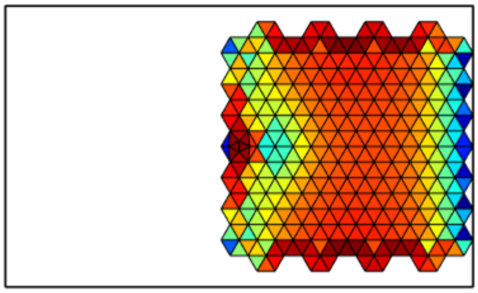

Fig. 1. Reference: square patch with optimized probe position; the rectangle overlay indicates the optimization domain used henceforth in machine design.

ACKNOWLEDGMENTS

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APPENDIX
PROOF OF THE ZONKLAR EQUATIONS

Use `\appendix` if you have a single appendix: Do not use `\section` anymore after `\appendix`, only `\section*`. If you have multiple appendixes use `\appendices` then use `\section` to start each appendix. You must declare a `\section` before using any `\subsection` or using `\label` (`\appendices` by itself starts a section numbered zero.)

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[1] J. Leonardo Araque Quijano and G. Vecchi, ”Optimization of an Innovative Type of Compact Frequency-Reconfigurable Antenna,” in IEEE Transactions on Antennas and Propagation, vol. 57, no. 1, pp. 9-18, Jan. 2009, doi: 10.1109/TAP.2008.2009649.

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[3] A. Bondy, U.S.R Murty ”Graph Theory”, 1st Edition, Springer London, 2008

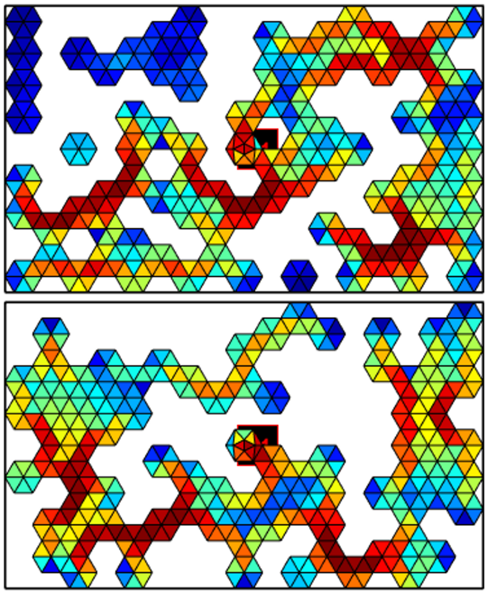

Fig. 2. Top: optimization of realized gain only; Bottom: optimization of the realized gain and simple connectivity together

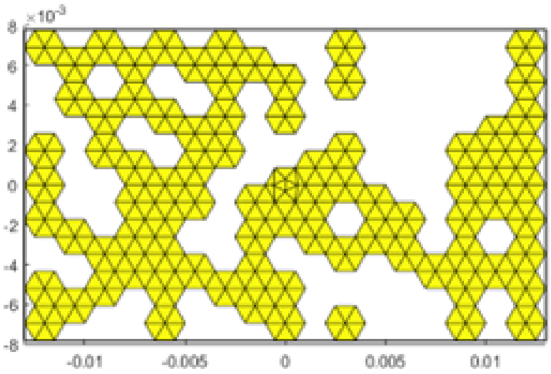

Fig. 3. Solution with aperture efficiency less than 0.80

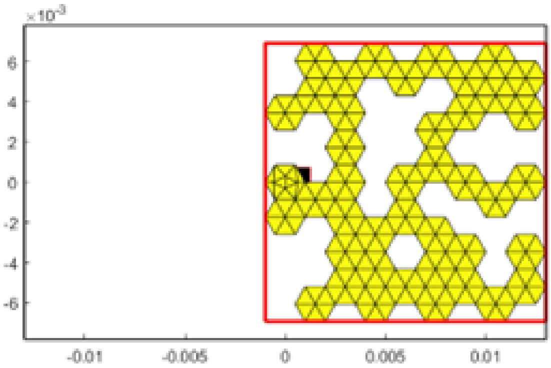

Fig. 4. Solution with aperture efficiency greater than 0.80 starting from a random initial population

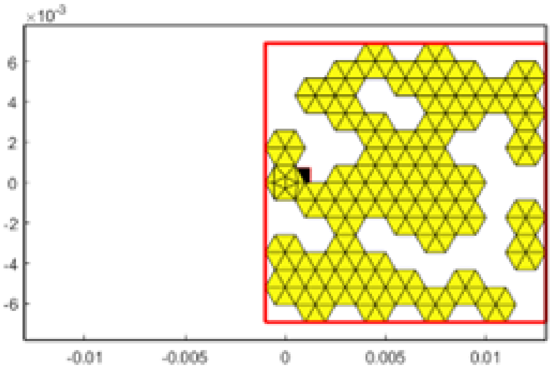

Fig. 5. Solution with aperture efficiency greater than 0.80 starting from the chromosome of the square patch in the first generation

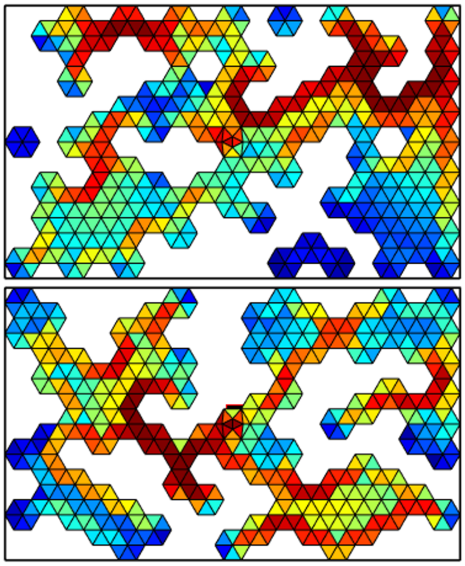

Fig. 6. Top: optimization of total aperture efficiency; Bottom: of total aperture efficiency and simple connectivity

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