Design of Optimal GPR Antennas for Concrete Evaluation

L. Travassos, *Student Member, IEEE*, S. Avila, N. Ida, C. Vollaire and A. Nicolas

***Abstract*— In order to resolve closely spaced targets in a planar surface normal to the beam, the antenna used in the radar assessment of concrete structures should have a narrow beam width which means a higher directivity. To optimize the field pattern of an antenna it was implemented a procedure that unifies multi-objective genetic algorithms (MGA) and a moment method (MoM) direct solver with the goal of implementing a tool capable to choose optimal parameters to achieve the design of an improved antenna to the radar testing of concrete structures.**

***Index Terms*— Optimization, antennas, non-destructive testing.**

I. INTRODUCTION

SINCE the success of the maintenance of a nation infrastructure depends on the ability of government policy makers to strike a balance between available funds and the need for repair or replacement, the Ground Penetrating Radar (GPR) inspection of concrete structures is increasingly being recognized as an effective way of maintenance.

This is due to the fact that tools for detecting distress that results from deterioration have had undesirable limitations in the past and these same limitations extend to the detection of cracks and flaws. These limitations include requirements for prolonged structures and significant measurement uncertainty.

Meanwhile, the life cycle cost of maintaining concrete structures increases when distress is not detected before it becomes too severe for effective repair or rehabilitation.

Antennas are one of the most critical parts in GPR systems. They substantially determine the quality of the obtained GPR raw data [1].

For work on concrete two main types of antenna are used, generally described as either dipoles that operate in close proximity to the material to be surveyed or TEM horns that operate at least one wavelength from the material. Most commercial GPR antennas are bow-tie dipoles given their loss weight, low cost and broadband characteristics.

However bow-tie antenna provides a dipole-like omnidirectional pattern with broad main beams perpendicular to the plane of the antenna. Consequently, the image created by a radar assessment could not correspond to the actual target, and closely-space objects can not be detected.

In this paper, we present an alternative way to design more efficient bow-tie dipole antennas using multi-objective optimization process [2].

Multi-objective optimization seeks to optimize the components of a vector-valued cost function. Unlike single objective optimization, the solution to this problem is not a single point, but a family of efficient points called Pareto optimal front which represents the trade-off among objective functions.

This procedure searches to attend two objectives: to minimize the metal area of the antenna (in order to reduce the size) and to maximize the gain in the plane normal to the antenna. The moment method (MoM) with Rao-Wilton- Glisson (RWG) basis functions [3] is used to calculate the electromagnetic characteristics of the antenna.

II. MODELING NEEDS

Computers have had a significant impact on the modeling of non-destructive testing (NDT) phenomena. In the method of numerical modeling a physical phenomenon under investigation is represented by a mathematical system which can be solved numerically. The results obtained from the mathematical investigation of such a model are then interpreted in terms of the original phenomenon and serve to develop an understanding of the physical processes involved. The most important task in NDT modeling is the prediction of faults or inclusions in the physical parameters characterizing the region under test.

NDT modeling involves calculating a physical magnitude i.e. electromagnetic field, force, radiation, in a model defined by a postulated distribution of parameters in the medium under study, together with the exciting source. This calculus can be done by solving finite-difference and finite-element equations. Concerning this work, the fundamental mathematical model is represented by Maxwell's equations, which prescribe the analytical relationship in the form of a system of first order vector equations between the components of electric and magnetic fields and the parameters of the medium under test.

The design of radar systems has been subjected to fundamental changes. Electronic devices are no longer designed on a simple desk using tables and calculators with inevitable design errors eliminated tediously on prototypes. Today, the design is computer aided, and both highly complex radars and complete electronic systems are simulated immediately. Design errors are excluded by a great deal by simulation. In reality, no designer and no simulation is perfect, so failures will still be detected on prototypes. However, the number of redesigns at the prototype stage has dropped in a sensible scale.

Traditionally the NDT modeling seeks at improving the systems' sensors design and provide data for imaging. Imaging of defects in concrete structures plays an important role in NDT. They are usually applied to pulse-echo data carried out by either acoustic, elastic or electromagnetic waves.

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Antenna design is a topic of great importance to electromagnetics. It involves the selection of antenna physical dimensions to achieve optimal gain, pattern performance, voltage standing-wave ratio, bandwidth, and so on, subject to some specified constraints.

A trial and error process is typically used for antenna design and consequently the designer is required to have great experience and intuition.

In the last decade, several investigators have reported encouraging results from the coupling of gradient-free methods with method of moments. The combination of various optimization methods and numerical techniques further enables the optimization of planar antennas such as a bow-tie shape using gradient or gradient-free optimization methods.

Gradient-free methods, or direct-search methods, are generally robust and particularly effective for problems with a large number of design variables, but require fast objective function evaluations for their practical implementation. They are largely independent of the initial design and solution domain. Therefore, global optima are more likely to be found. As is generally understood, gradient-free methods work very well when many local optima exist, whereas gradient-based methods break down in these cases.

III. MULTI-OBJECTIVE GENETIC ALGORITHM

The Genetic Algorithm (GA) is a stochastic procedure based on the concepts of natural selection and genetics. There are many papers showing the effectiveness of the GA to solve engineering optimization problems.

In most real-world problems, several goals must be satisfied simultaneously in order to obtain an optimal solution. As these objectives are usually conflicting, no single solution may exist that is best regarding all considered criteria.

Multi-objective optimization (also called multicriteria, multiperformance or vector optimization) seeks to optimize the components of a vector-valued cost function. Unlike single objective optimization, the solution to this problem is not a single point, but a family of efficient points.

Each point in this set is optimal in the sense that no improvement can be achieved in a cost vector component that does not lead to degradation in at least one of the remaining components. Each element in the efficient set constitutes a non-dominated (non-inferior or non-superior) solution to the multi-objective problem.

The main action of the multi-objective optimization is to determine the efficient front. With this set of solutions, it is possible to understand the dependence between each objective, which allows making efficient choices for the final solution decision.

The analysis of the Pareto-front behavior permits to understand the tradeoff between the different objectives. Compared with the deterministic optimization methods, which lead to unique solution, multi-objective genetic algorithms (MGA) offers the possibility to the designer to make the final choice among the set of solutions by considering additional constraints not included in the initial steps [2,4].

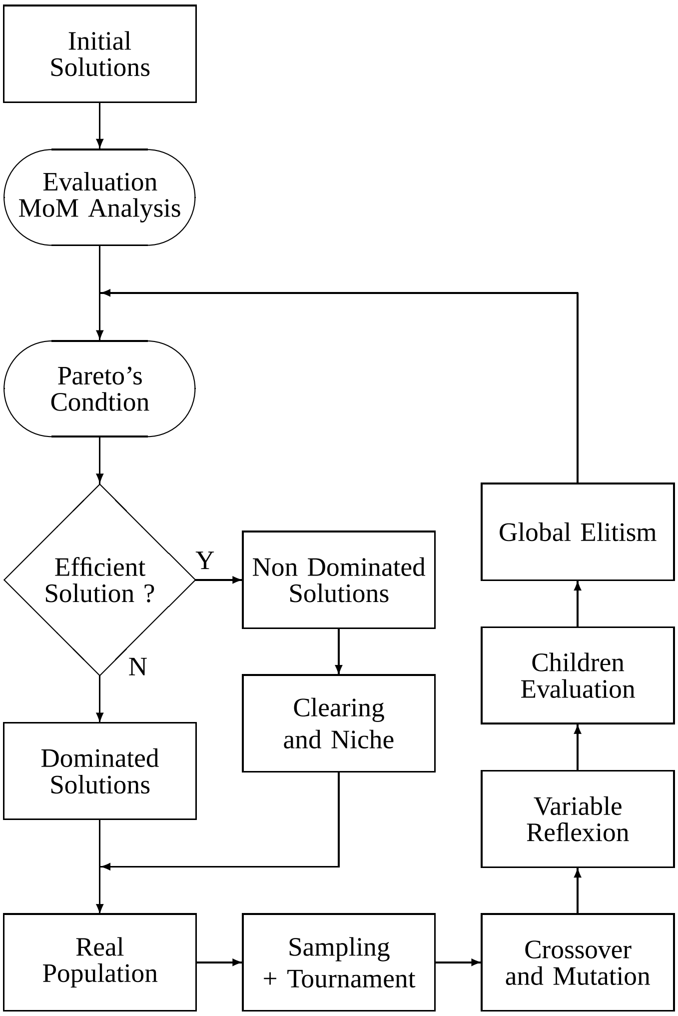

Fig. 1. Multi-objective Genetic algorithm.

The MGA used in this work is based on three current populations. Basically, the algorithm starts with a set of solutions randomly created. These solutions are evaluated and the Pareto-optimal condition is tested, giving two groups of solutions: one formed by efficient solutions, called non-dominated population (NDOM); and another by non-efficient solutions, called dominated population (DOM).

An index (IDOM) indicating how many times each solution is dominated by others is created. After the Pareto's check, it is time to apply the Clearing technique, whose purpose is to obtain a sparse and well-established Pareto front. If similarities among individuals are detected (in parameters or/and objectives spaces [5]), one or some of them are punished. The penalty consists in moving the penalized individual to DOM (by changing IDOM from 0 to 1).

This approach makes easier the attainment of a well-established Pareto set. Crossover and mutation operators based on real coding representations are then applied to create the children of a generation.

To control that all design variables always remain inside the feasible bounds and are not affected by the evolutionary process, a procedure of ”adjustment by saturation” is applied. Design variables outside their prescribed limits are automatically adjusted to the limit values.

The children are evaluated and associated with the non-dominated solution of REAL to form the new initial population. This elitism process guarantees the preservation of efficient parent solutions. The process is iterated until an ending criterion is met (typically a fixed number of generations).

IV. RESULTS

Bow-tie antennas are not isotropic radiators or receivers and exhibit directionality of wavefields. High directivity adversely affects wide angle surveys used to determine velocity and other physical attributes.

In addition, directivity becomes even more important for imaging applications used to accurately determine the shape, location, and size of subsurface targets and becomes essential when inverting GPR data to extract target's physical properties.

The design of an effective planar bow-tie antennas requires balancing the antenna length, the flare angle and the radiation pattern produced. Therefore, there is an issue of optimization in determining the antenna parameters for best performance. To address the issue of optimization, we considered the problem where an antenna is in free-space and evaluated in the far-field region.

Most antenna characteristics that are relevant to GPR applications such as the wave polarisation, radiation field pattern and beam width are commonly defined in the far-field region of an antenna.

However, notwithstanding the complexity of the electromagnetic radiation in the near-field region, most civil engineering applications using surface contact antennas are concerned with radar measurements in the near-field region [6].

Considering this complexity, edge finite elements (FEM) are used to investigate the behaviour of the optimized antenna in the near-field region of a concrete GPR assessment to the location of reinforced bars.

The goal in the optimized design of this antenna is to reduce the metal area (and consequently a minimal length and weight) and to improve the gain in the plane perpendicular to the antenna. The MGA are then coded to find multiple non-dominated solutions (the Pareto-front) using a fixed frequency of 1 GHz. The antenna parameters to adjust are:

$$P^g = \begin{bmatrix} L^{g,1} & \alpha^{g,1} & E^{g,1} \\ \vdots & \vdots & \vdots \\ L^{g,np} & \alpha^{g,np} & E^{g,np} \end{bmatrix} \tag{1}$$

where each line represents a feasible solution, g is the current generation and np is the population size. The variables to be optimized are then the antenna length, the flare angle and the percentage of antenna elements that can be erased. They are adjusted to minimize the metal area of the antenna. This becomes the first objective function. The second objective function is to maximize the gain in the direction perpendicular to the antenna plan.

In order to find the antenna configuration with a higher directivity and a smaller metal area we implemented a MGA to accomplish two conflicting objectives with the following limits: the length L [0.1λ to 1λ] (with frequency equal to 1 GHz), the flare angle [30° to 120°], and the void spaces in the antenna structure.

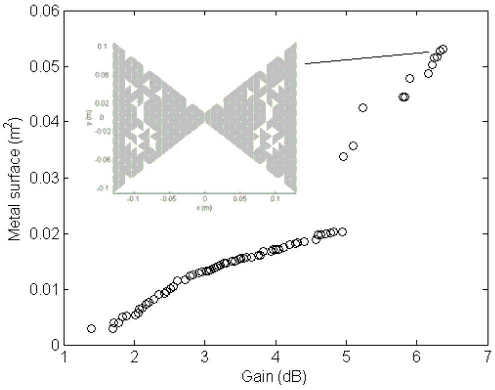

Fig. 2. Pareto front for the planar bow-tie antenna.

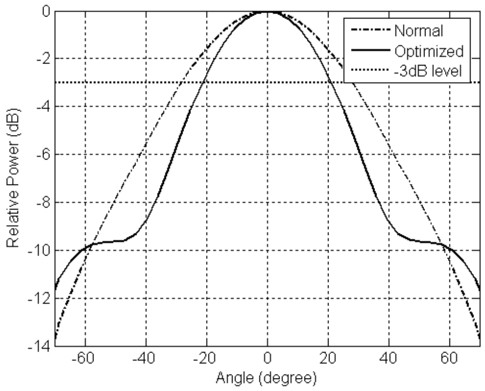

Fig. 3. H-plane field pattern of the planar bow-tie antenna.

The antenna first is created with 256 elements and then a percentage of this total between 0 and 20% is replaced from metal to air according to the objectives. The feed region is obviously protected to avoid numerical errors.

Figure 1 shows the pareto-front and the modifications applied to a given solution in order to improve the radiation pattern. The optimized antenna proposed by the algorithm with a maximal gain has α=79° and L=26cm with 11% of the elements erased.

The radiation pattern shown in the Figure 2 presents the gain obtained in the plane normal to the antenna. The gain obtained was 6.37 dB against 3.40 dB of a common structure with improvement of the half-power beam width from 57.6° to 43.2°. In this case, the area presented is maximal. Other soulutions can be found according with the designer's needs.

The convergence has been attained in about 50 generations with a population of 50 individuals in several GA executions. The crossover and mutation probabilities were set to 0.9 and 0.05 respectively.

To take into account the coupling effects of the antenna on a dielectric interface FEM are useful due to their correct physical sense and accuracy. Considering this, the electromagnetic propagation of a more realistic model of concrete structure was realized using FEM.

TABLE I
DATA FOR THE CONCRETE PROBLEM

Porosity of concrete	0.15
Degree of saturation	0.7
Salt content	52ppt
Temperature	20°C

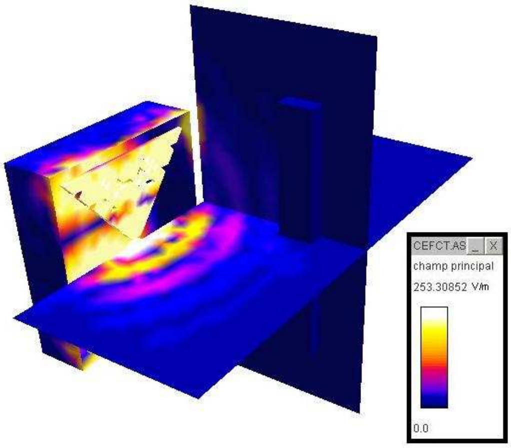

Fig. 4. Finite element analisys of the optimized antenna.

For the concrete electrical properties, the discrete model proposed by Halabe [7] was used. This model deals with complex conductivities instead of complex dielectric constants. The discrete model is then used to compute the complex pemittivity for each frequency component.

The concrete electrical properties used are shown in Table I. In addition, it was added to the antenna a conductor shield to improve the directivity. For 1 GHz the concrete slab was simulated with $\epsilon_r = 8.37$ and $\sigma = 0.23S/m$. First order boundary conditions were used to truncate the domain of study. The simulation was performed in a Pentium IV with 964Mb in about 15 min for a domain of 25K nodes.

The scattered near field shown in Figure 3 illustrates a non-destructive assessment to detect the presence of a conducting bar buried 15 cm in the concrete and located parallel to the antenna's direction.

Figure 4 shows the modifications in the antenna's input impedance for three different scenarios. In the case where the bar is perpendicular to the antenna, and consequentially, located in the region more illuminated, the input impedance is more affected indicating his presence.

In order to improve the results, it was added to the problem the angle between the bow-tie wings as a new variable. The pareto-front for the V-shaped bow-tie antenna is shown in Figure 5 with the geometry of the solution with a maximal gain. At this time, a new constraint was imposed to problem: the return loss of the antenna.

Antennas with a return loss greater than -10 dB considering a transmission line feed with 200 Ω were penalized in the optimization process. The gain obtained was of 8.77 dB with a return loss of -13.5 dB for 1 GHz. The angle between the bow-tie wings found was 97.88°. In this case, the same antenna without the holes would not fulfill the impedance criteria.

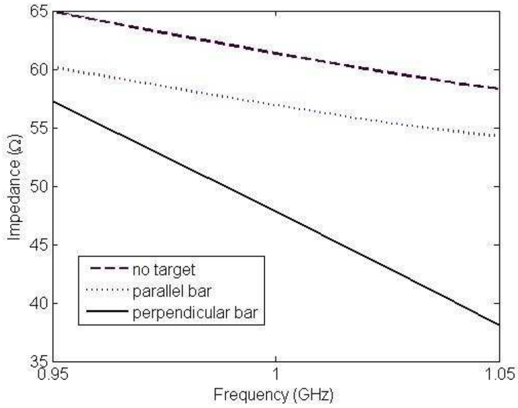

Fig. 5. Input impedance of the antenna in the radar assessment.

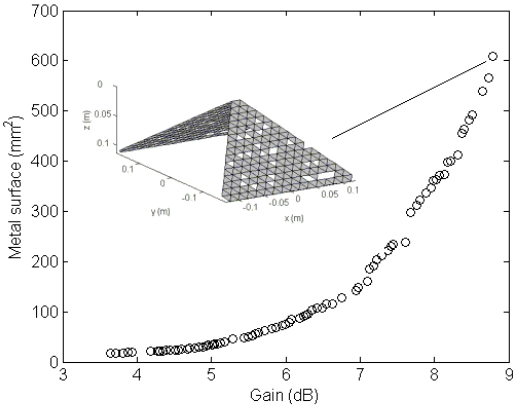

Fig. 6. Pareto front for the V-shaped bow-tie antenna.

V. CONCLUSION

The significance of this antenna pattern optimization approach is in the resolution that can be achieved in improving the antenna design. The results show that a better field pattern can be obtained with the optimized antenna which leads to a better signal penetration and more realistic GPR images of lossy concrete structures.

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