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Surrogate-Assisted Optimization of Metamaterial Devices for Advanced Antenna Systems

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***Abstract*—The synthesis of metamaterial devices able to enhance the features (radiation, size, etc.) of advanced antenna system is addressed in this work through an innovative surrogate-assisted optimization strategy. The design technique, which belongs to the class of System-by-Design methodologies, integrates a multi-agent cooperative evolutionary optimization technique with a surrogate model used to predict the value of the cost function (mismatch between desired and obtained radiation features) without requiring full-wave numerical simulations at each iteration of the iterative search procedure. The effectiveness of the introduced approach is preliminary validated in the design of an inhomogeneous isotropic metamaterial lens devoted to the miniaturization of a linear array.**

I. INTRODUCTION AND MOTIVATION

The synthesis of advanced antenna array systems for communications and radar applications often requires the designer to comply with complex and contrasting constraints in terms of sidelobe control, weight, and number of transmit-receive modules (TRM) employed in the feed network [1][2]. The possibility to miniaturize the array aperture or number of control points [1]-[5] therefore represents a fundamental challenge in advanced antenna design, and several methodologies have been proposed in the literature towards this end which are usually based on non-uniform geometries [1]-[10]. Nevertheless, synthesis solutions that are able to both reduce the aperture width and the number of TRM in advanced antenna systems have been seldom addressed in the scientific community.

In this framework, the exploitation of innovative materials belonging to the broad class of metamaterials [11][12] has been recently proposed for the design of advanced antenna systems [13][14], and the possibility to combine aperture miniaturization and reduction of the number of control points in linear phased arrays through the exploitation of inhomogeneous metamaterial lenses has been demonstrated [15]. In this case, the key idea is that a metamaterial radome covering the phased array can be designed to manipulate the field so that the array radiates as a wider one comprising more elements. To achieve this goal, a transformation electromagnetics strategy has been adopted because of its effectiveness in handling the design of complex metamaterial lenses without requiring iterative optimization procedures [11]-[14]. Indeed, synthesizing an advanced antenna system comprising a metamaterial lens can be computationally unfeasible with standard optimization techniques, because of their need to simulate several candidate solutions (through a full-wave solver) in order to suitably explore the available solution space. Unfortunately, transformation electromagnetic tools can yield complex anisotropic material properties (with very high or very low permittivity values) in the lens, thus affecting the actual realizability of the designed advanced antenna systems.

In order to address these issues, the exploitation of surrogate-assisted methodologies belonging to the System-by-Design paradigm has been proposed [16]-[18]. The fundamental idea behind surrogate-enhanced optimization is that, under certain conditions, the evaluation of the cost function (required in the search procedure) can be performed by a fast Metamodel (based on a learning-by-example paradigm) instead of exploiting expensive full-wave numerical simulators [16]-[19]. Thanks to this approach, the design of extremely complex devices can be carried out almost in real time [16]-[18].

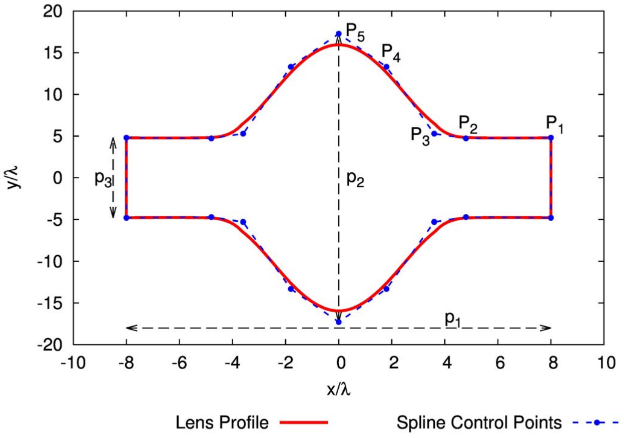

Fig. 1. Parametrized Virtual Lens Profile.

In the following, such a surrogate-based optimization paradigm will be applied to design advanced antennas that overcome the limitations of the devices proposed in [15]. To this end, the degrees-of-freedom enabled in the definition of the so-called “virtual geometry” (arising in the array synthesis problem formulated in [15]) will be exploited by parametrizing

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its contour through a spline-shaped function, whose descriptors will be then considered as the optimization variables. Moreover, the associated cost function will comprise a terms regarding the mismatch between the field radiated by the large arrays radiating in free space and the small array (with fewer elements) covered with the radome, and a term concerning the maximum relative permittivity value of the synthesized radome. Preliminary numerical results will be provided to validate the proposed algorithm.

II. PROBLEM FORMULATION AND SURROGATE-ASSISTED DESIGN METHODOLOGY

Consider a reference linear equally-spaced arrangement including N_v radiators located at position $\mathbf{r}_n = \left(x_n = 0, y_n = (n-1)d_v - \frac{L_v}{2} \right)$ where d_v is the inter-element spacing and L_v is the *virtual* array length. The goal of the surrogate-assisted design methodology is to synthesize an array that radiates a field $E(\mathbf{r})$ as close as possible to that radiated by the reference one but with a reduced number of elements $N_p < N_v$ and a reduced aperture $L_p = (N_p - 1)d_p < N_v$. In addition, the relative permittivity of the synthesized lens should be as close as possible to 1.

To address this problem, an iterative optimization loop is considered which exploit the transformation electromagnetics framework [15] and combines it with a surrogate-enhanced cost function evaluation process [16]-[18]. More in detail:

- Transformation electromagnetics require the definition of a virtual and a physical geometry [11]-[14]. In such a case, analogously to [15], the physical geometry is defined as the target lens contour, while the virtual one is represented by a "air box" of arbitrary shape surrounding the reference arrangement [15]; the problem is thus related to finding the physical lens relative dielectric properties and the array excitations such that the field radiated by the array coated with the lens radiates a field $E(\mathbf{r})$ as close as possible to the reference one.
- The virtual geometry contour is discretized using the spline descriptors reported in Fig. 1 (i.e., $\mathbf{q} = \{p_1, p_2, p_3, P_1, \ldots, P_5\}$).
- Because of the continuous nature of the design variables, and because of the high nonlinearity of the cost function, the search procedure is based on the inertial-weight version of the particle-swarm (PS) approach.

The problem cost function $\Phi(\mathbf{q})$ contains multiple terms regarding the mismatch between the fields radiated by the N_v-elements array in free space and by the N_p-elements array coated with the spline-enhanced metamaterial lens, as well as the final lens properties. In particular, it is defined in the following way:

$$\Phi(\mathbf{q}) = \frac{\alpha_1 \psi_{HPBW} + \alpha_2 \psi_{FNBW} + \alpha_3 \psi_{SLL} + \alpha_4 \psi_{\rho} + \alpha_5 \psi_{\varepsilon_{\max}}}{\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_5} \qquad (1)$$

where $\psi_{HPBW} = |HPBW' - HPBW|$ and $\psi_{FNBW} = |FNBW' - FNBW|$ are the half-power beamwidth and first-null beamwidth deviations from the corresponding virtual quantities, $\psi_{\rho} = |\rho' - \rho^{target}|$ is the array compression ratio deviation from a target value, $\psi_{SLL} = SLL'$ and $\psi_{\varepsilon_{\max}} = \varepsilon'_{\max}$ are the sidelobe level and maximum relative permittivity values and $\alpha_k, k = 1, \ldots, 5$ are user-defined weights. Finally, a Learning-by-Example (LBE) regression strategy (belonging to the class of Gaussian Process (GP) [17]) is adopted to compute (1) without performing expensive full-wave simulations at each iteration of the optimization process. More in details, thanks to an off-line training phase, it is possible to predict (1) in a computationally efficient and accurate way [19] without requiring a continuous call to the full-wave solver.

III. PRELIMINARY NUMERICAL VALIDATION

In order to preliminarily assess the validity of the proposed method, let us consider a reference array considered in [15] which comprises $N_v = 30$ uniformly-excited elements with inter-element spacing equal to $d_v = \frac{\lambda}{2}$. The virtual array length is thus equal to $L_v = 14.5\lambda$. The radiated pattern is represented in Fig.2 (red line).

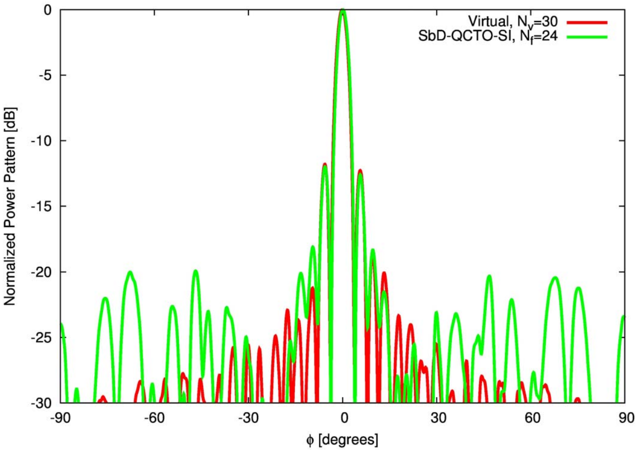

Fig. 2. Power patterns radiated by the *virtual* and the miniaturized configurations

The proposed synthesis methodology has been applied; as for the control parameters of the inertial-weight version of the particle-swarm approach, the swarm dimension has been set equal to $S = 8$, the maximum number of iterations to $I = 200$, the user-defined stagnation threshold and the window to $\eta = 10^{-4}$ and $I_{win} = 30$, respectively [20]. The plot of the final layout comprises only $N_p = 24$ non-uniformly excited elements spanning a reduced aperture ($\rho = \frac{L_p}{L_v} = 0.79$). Moreover, the lens synthesized using the proposed approach yields a reliable control of the mainlobe width ($\psi_{HPBW} = 2.8\times10^{-2}$) and of the envelope of the first sidelobes ($SLL' = 11.98$ dB while $SLL^{virtual} = 11.8$ [dB]), as can be noticed analyzing the far field pattern in Fig. 2. Furthermore, the maximum permittivity value is only $\varepsilon_{\max} = 2.1\times10^{1}$, as can be observed looking at the isotropic nonmagnetic relative permittivity ε_r shown in Fig. 3. Thus value is significantly lower than that of the lenses synthesized in [15], where $\varepsilon_{\max} > 2.2\times10^{2}$.

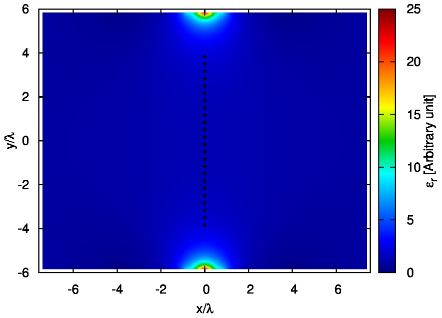

Fig. 3. Relative permittivity distribution ε_r of the isotropic synthesized lens layout.

IV. CONCLUSIONS

An innovative strategy which exploits a surrogate-enhanced optimization loop has been presented for the synthesis of advanced antenna systems comprising complex metamaterial lenses. The effectiveness of the arising technique has been preliminarily validated in the design of miniaturized arrays featuring non-homogeneous isotropic lenses, demonstrating its effectiveness and flexibility.

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