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EVOLUTIONARY TECHNIQUES FOR INVERSE SCATTERING – CURRENT TRENDS AND ENVISAGED DEVELOPMENTS

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Evolutionary Techniques for Inverse Scattering
- Current Trends and Envisaged Developments -

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Introduction

The possibility of sensing a given region from the measurements of the scattered field when it is illuminated through low-power microwave electromagnetic waves is still a topic of great interest due to the wide range of applications in many different areas of medical, industrial, and civil engineering. For instance, let us consider problems related to biomedical engineering, non-invasive thermometry, non-destructive testing and evaluation, geophysical analysis, remote sensing, and archeology. Although this list is certainly non-exhaustive, it is sufficient to justify the great attention devoted to the solution of inverse scattering problems both from a theoretical and algorithmic point of view, as demonstrated by the large amount of papers and books available in the scientific literature. The issues that actually limit the proliferation of practical imaging systems are the intrinsic theoretical difficulties (i.e., ill-posedness and non-linearity), which characterize an inverse scattering problem. The ill-posedness can be avoided by using additional (*a-priori*) information directly taken from the physics of the problem at hand. This strategy allows one to avoid the reconstruction of artifacts and obtain the so-called regularized solutions. Concerning the non-linearity of the inverse scattering model, it must be considered to take into account the multiple-scattering effects, since linear approximations (e.g., Born-like approaches) can be rarely applied to real objects. Accordingly, many non-linear inversion techniques have been proposed for the optimization of a suitable cost function taking into account the mismatch between the measured data and the reconstructed ones. Originally, various deterministic approaches based on steepest-descent algorithms [e.g., conjugate-gradients (CG)] were proposed [1]. Although they have shown to provide successful results, they suffer the presence of local minima when initial solution does not belong to the "attraction basin" of the global optimum.

In the last decades, thanks to the growing of the available computational capabilities given by modern personal computers, optimization techniques based on evolutionary algorithms (EAs) have received great attention and they have been effectively applied also to inverse scattering problems. EAs are based on stochastic iterative procedures which consider a pool of trial solutions at each iteration thus enabling an efficient sampling of the solution space as compared to single-agent stochastic optimization algorithms (e.g., Simulated Annealing [2]). The pool of solutions iteratively updates through the use of proper

operators/rules until a convergence criterion is reached based on a threshold on the cost function or on a maximum number of iterations. Among the EAs which have been effectively used in electromagnetics, it is worth mentioning the class of the genetic algorithms (GAs), the differential evolution (DE) strategies, the memetic algorithm (MA), and the approaches based on swarm intelligence, namely the particle swarm optimization (PSO) and the ant colony optimization (ACO). EAs have shown many attractive features suitable for dealing with inverse scattering problems. More specifically, they are hill-climbing algorithms which not require the differentiation of the cost function, which is a must for gradient-based methods. Moreover, *a-priori* information can be easily introduced, usually in terms of additional constraints on the actual solution, and they can directly deal with real values as well as with a coded representation of the unknowns (e.g., binary coding). As regards to the architecture of the implementation, they can be effectively hybridized with deterministic procedures. Furthermore, they are particularly suitable for parallel computing. Despite several positive advantages offered by the EAs, further researches are required in this framework to overcome the well-known drawbacks affecting these approaches. More specifically, the high computational load and the low convergence rate should be avoided especially when dealing with either high-resolution 2D imaging or 3D imaging problems due to the number of unknowns.
This paper is aimed at giving a short overview on current trends and envisaged developments of Eas in the framework with reference to the activities carried out from long time now at the ELEDIA Gorup in Trento.

EAs-based Strategies for Inverse Scattering

Although EAs are characterized by several good properties, some countermeasures have been studied in the last years to limit or avoid their drawbacks in order to fully exploit their potentialities in dealing with non-linear inverse scattering. Because of the complexity of the problem at hand as well as of the articulated structure of an EA-based imaging technique, the research work has is carried out at different levels:

- at the operator’s level by modifying the EA standard operators in order to take into account the landscape of the cost function to be minimized in order to improve the convergence rate;
- at the architectural level, hybridizing stochastic algorithms with deterministic methods in order to exploit the complementary advantages of the two methodologies in terms of global optimization of the EAs and fast convergence rate of the CG;
- at the system level, changing from a serial to a parallel implementation in order to reduce the computational time of the inversion process;
- at the architectural level for allowing an enhancement in the spatial resolution through the integration of global optimizers with a multi-resolution strategy.

The ELEDIA research group at the University of Trento has been involved in those issues from several years and some solution recently proposed are shortly summarized in the following.
As far as the evolutionary operators are concerned, the so-called parabolic crossover has been proposed in [3]. It exploits locally-quadratic nature of the cost non-linear mismatching function. Each updated solution is obtained as the vertex of the multidimensional “parabola” passing through three trial solutions of the previous population. In such a way, the convergence rate of the GAs turns out to be increased.
Another way for improving the convergence rate of the minimization is that of hybridizing EAs with gradient-based methods. In this framework, two different strategies can be adopted. First, EAs can be exploited for locating the attraction basin of the global minimum and the gradient based minimization is performed in order to determine its minimum. In this case, the main problem is the definition of the switching criterion since they do not provide analytical criterions to state if the attraction basin of the global minimum was reached. Thus, in order to avoid the need of a switching criterion and to improve the convergence rate through the coupling between deterministic/stochastic algorithms, a step-by-step approach has been proposed [4]. More in detail, at each iteration of the real-GA, the best solution is identified and used as initial solution for a CG-based minimization loop. At the end, the rael-GA population is updated according to the classical operators and the iterative loop is repeated.
On the other hand, the runtime of EAs can become easily unacceptable in serial implementations, thus preventing their use in real-time or quasi-real-time applications. Besides the use of hybridized algorithms (to speed up the convergence rate), the exploitation of the intrinsic parallelism nature of global optimization procedures is very suitable for a parallel implementation [5] because of the explicit parallelism of EAs due to the multiple-agent nature of the optimization process.
As regards to the EAs efficiency, it is well known that stochastic optimizers perform in a very effective fashion when a reduced set of unknowns is at hand. Since the available scattering data collectable during an inverse scattering experiment defines an upper bound to the achievable spatial resolution in a reconstruction, integration with a multi-resolution procedure is certainly a good recipe to improve the imaging process. Thanks to a “smart allocation” of the problem unknowns, a high spatial resolution is requested only in those regions where the scatterers are supposed to be located. Towards this end, the IMSA (Iterative Multi-Scaling Approach) has been integrated with a PSO strategy in [6] for 2D inverse scattering problems and, more recently, its effectiveness in dealing also with 3D scenario with several unknowns has been also assessed [7].

Discussion and Conclusions

Concerning the state-of-the-art of the application of EAs to inverse scattering, it should be firstly pointed out that their use in computational electromagnetics has a relatively short history, although their use was growing faster from the beginning. However, many of these algorithms (e.g., PSO [8] and ACO [9]) cannot be considered fully developed inversion techniques when compared to other imaging methodologies. From a theoretical point of view, a further analysis concerned with the convergence issues is certainly mandatory. As a matter of fact, the stochastic nature of EAs is an effective feature, but on the other hand it is also a non-negligible obstacle for industrial applications because the non-predictable performances.

Nevertheless, even though further developments are still required, existing EAs strategies already demonstrated their potential impact in dealing with complex and large-scale inversion problems. The flexibility of these algorithms and their key features fully justify the large effort dedicated to the development of EA-based techniques for microwave imaging applications [10].

References

[1] P. M. Van den Berg and A. Abubakar, "Contrast source inversion method: state of the art," *PIER*, vol. 34, pp. 189-218, 2001.

[2] L. Garnero et al., "Microwave imaging-complex permittivity reconstruction-by simulated annealing," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 1801–1807, 1991.

[3] A. Massa et. al., "Improving the effectiveness of GA-based approaches to microwave imaging through an innovative parabolic crossover," *IEEE Antennas Wireless Propag. Lett.*, vol. 4, pp. 138-142, 2005.

[4] A. Massa et al., "A computational technique based on a real-coded genetic algorithm for microwave imaging purposes," *IEEE Trans. Geosci. Remote Sens.*, vol. 38, no. 4, pp. 1697-1708, Jul. 2000.

[5] A. Massa et al., "Parallel GA-based approach for microwave imaging applications," *IEEE Trans. Antennas Propag.*, vol. 53, no. 10, pp. 3118-3127, Oct. 2005.

[6] M. Donelli et al., "An integrated multiscaling strategy based on a particle swarm algorithm for inverse scattering problems," *IEEE Trans. Geosci. Remote Sens.*, vol. 44, no. 2, pp. 298-312, Feb. 2006.

[7] M. Donelli et al., "Three-dimensional microwave imaging problems solved through an efficient multiscaling particle swarm optimization," *IEEE Trans. Geosci. Remote Sens.*, accepted for publication.

[8] M Donelli and A. Massa, "A computational approach based on a particle swarm optimizer for microwave imaging of two-dimensional dielectric scatterers," *IEEE Trans. Microwave Theory Techn.*, vol. 53, no. 5, pp. 1761-1776, May 2005.

[9] M. Brignone et al., "A hybrid approach to 3D microwave imaging by using linear sampling and ACO," *IEEE Trans. Antennas Propag.*, vol. 56, no. 10, pp. 3224-3232, Oct. 2008.

[10] A. Massa et al., "A microwave imaging method for NDE/NDT based on the SMW technique for the electromagnetic field prediction," *IEEE Trans. Instrum. Meas.*, vol. 55, no. 1, pp. 240-147, Feb. 2006.