Microwave Imaging of Dielectric Cylindrical Target Using Dynamic Differential Evolution and Self-Adaptive Dynamic Differential Evolution

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Abstract: The inverse problem under consideration is to reconstruct the characteristic of scatterer from the scattering E field. Dynamic differential evolution (DDE) and self-adaptive dynamic differential evolution (SADDE) are stochastic-type optimization approach that aims to minimize a cost function between measurements and computer-simulated data. These algorithms are capable of retrieving the location, shape and permittivity of the dielectric cylinder in a slab medium made of lossless materials. The finite-difference time-domain (FDTD) is employed for the analysis of the forward scattering. Numerical results indicate that both optimization methods are reliable tools for inverse scattering applications. In the particular case of small-scale problems investigated in this paper, SADDE outperforms the DDE a little in terms of reconstruction accuracy.

Keywords: ***Inverse Scattering, Differential Evolution, Optimization.***

1 INTRODUCTION

The inverse scattering scattering problem of unknown objects has many applications including microwave imaging, ground penetrating radar, nondestructive evaluation, and biomedical engineering. Numerous inverse problem techniques for 2-dimensional or 3-dimensional targets were reported [1]-[10].

For example, single frequency plane waves at a fixed angle were used in [1] to illuminate the perfect electric conductors (PEC), and the observation domain was located in the far zone. Upon using a linear distributional model, the unknown parameters were retrieved. A Kirchhoff-based approximation was employed in [2] to retrieve the shape of 2-D dielectric cylinders from aspect-limited multi-monostatic backscattering data. The Tikhonov regularized Gauss-Newton framework was implemented in [3] to reconstruct the boundary and the inhomogeneity parameters of 2-D scatterers. For the breast cancer application, the shape and the location of a 3-D breast cancer tumor-like were retrieved using the spherical harmonic decomposition approach [4]. The gradient descent optimization method and the Method of Moments (MoM) were combined to determine the coefficients of the spherical harmonic decomposition. A lossless dielectric 2-D object with irregular shape was simulated nondestructive evaluation [5]. However, these papers are focused on frequency-domain.

As compared to frequency-domain approach, the interaction of the entire medium in the time domain with the incident field needs to be considered. In contrast, time-domain approaches can exploit causality to limit the region of inversion, potentially reducing the number of unknowns. The genetic algorithm (GA) was reported as a fast and very effective technique for shape reconstruction problems [6]. In this method, the shape of the scattering object was retrieved upon solving cost function. However, large amount of computation load was generally needed. Improvements in the GA were reported in [7] where good reconstruction results were demonstrated using fewer searching time. Optimization methods, such as the synchronous particle swarm optimization (SPSO) techniques were reported in [8] where the shape of 2-D PEC target was reconstructed using the asynchronous particle swarm optimization (APSO). In the 2010, the dynamic differential evolution (DDE) was first proposed to deal with the shape reconstruction of homogeneous dielectric cylinders under time domain [9]. The DDE algorithm is a potentially trend to obtain the global optimum of a functional whatever the initial guesses are. In recent decade years, some papers have compared different algorithm in inverse scattering [10]-[15]. To the best of our knowledge, there is still no comparative study about the performances of SADDE and DDE to inverse scattering problems is also investigated. I n this paper, the computational methods combining the FDTD method [16] and the DDE and SADDE is presented. The forward problem is solved by the FDTD method. The shape of scatterer is parameterized by closed cubic spline expansion. The inverse problem is formulated into an optimization one and then the global searching scheme DDE and SADDE is used to search the parameter space. In section II, the subgridding FDTD method for the forward scattering are presented. In sections III and IV, the inverse problem and the DDE and SADDE of the proposed inverse problem are given, respectively. In V section, the numerical result of the proposed inverse problem is given. Finally, in VI section some conclusions are drawn for the proposed time domain inverse scattering.

.2 FORWARD PROBLEM

Let us consider a two-dimensional metallic cylinder buried in a slab medium as shown in Figure 1. The cylinder is parallel to z axis, while the cross-section of the cylinder is arbitrary. The object is illuminated by a Gaussian pulse line source located at the points denoted by Tx and reflected waves are recorded at those points denoted by Rx. The computational domain is discretized by Yee cells. It should be mentioned that the computational domain is surrounded by the optimized perfect matching layers (PML) absorber to reduce the reflection from the environment-PML interface [17].

The direct scattering problem is to calculate the scattered electric fields while the shape and location of the scatterer are given. The shape function $F(\theta)$ of the scatterer is described by the trigonometric series in the direct scattering problem

$$F(\theta)=\sum_{n=0}^{N/2} B_n \cos(n\theta)+\sum_{n=1}^{N/2} C_n \sin(n\theta) \qquad (1)$$

where Bn and Cn are real coefficients to expand the shape function.In order to closely describe the shape of the cylinder for both the forward and inverse scattering procedure, the subgridding technique is implemented in the FDTD code; More detail on subgriding FDTD can be found in [16].

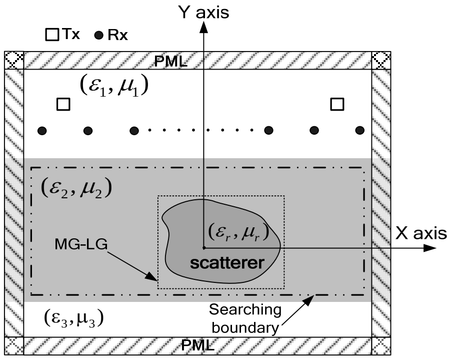

Fig. 1. Geometrical configuration of the problem.

3 INVERSE PROBLEM

For the inverse scattering problem, the shape and location of the perfectly conducting cylinder are reconstructed by the given scattered electric field measured at the receivers. This problem is resolved by an optimization approach, for which the global searching DDE and SADDE is employed to minimize the following objective function (*OF*):

$$OF=\frac{\sum_{n=1}^{N_i}\sum_{m=1}^{M}\sum_{q=0}^{Q}\left|E_z^{exp}(n,m,q\Delta t)-E_z^{cal}(n,m,q\Delta t)\right|}{\sum_{n=1}^{N_i}\sum_{m=1}^{M}\sum_{q=0}^{Q}\left|E_z^{exp}(n,m,q\Delta t)\right|} \qquad (2)$$

Where E_z^{exp} and E_z^{cal} are experimental electric fields and the calculated electric fields, respectively. The N_i and M are the total number of the transmitters and receivers, respectively. Q is the total time step number of the recorded electric fields.

4 EVOLUTIONAL ALGORTHEMS

DDE algorithm starts with an initial population of potential solutions that is composed by a group of randomly generated individuals which represents the center position and the geometrical radiuses of the cylinders. Each individual in DDE algorithm is a D-dimensional vector consisting of D optimization parameters. The initial population may be expressed by $\left\{x_j:\ \ j=1,\ 2,\cdots,Np\right\}$, where Np is the population size. After initialization, DDE algorithm performs the genetic evolution until the termination criterion is met. DDE algorithm, like other EAs, also relies on the genetic operations (mutation, crossover and selection) to evolve generation by generation. The mutation operation of DDE algorithm is performed by arithmetical combination of individual. For each parameter vector x_j of the parent generation, a trial vector v_j is generated according to following equation:

$$(V_j^{g+1})_i=(X_j^g)_i+F\cdot[(X_{best}^g)_i-(X_j^g)_i]+\lambda\cdot[(X_{r1}^g)_i-(X_{r2}^g)_i],$$

$$r1, r2 \in [0, N_p - 1],\ r1 \neq r2 \tag{3}$$

where F and λ are the scaling factors associated with the vector differences $(\mathrm{X}^{g}_{best} - \mathrm{X}^{g}_{j})$ and $(\mathrm{X}^{g}_{r1} - \mathrm{X}^{g}_{r2})$, respectively. The disturbance vector V due to the mutation mechanism consists of parameter vector X^{g}_{j}, the best particle X^{g}_{best} and two randomly selected vectors. SADDE are based on DDE scheme. Each vector is extended with its own λ, F and *CR* values. Therefore the control parameters are self-adjusted in every generation for each individual according to the following scheme:

$$F_{i,G+1} = \begin{cases} F_l + rand_1 * F_u, & if \quad rand_2 < 0.1 \\ F_{i,G+1}, & otherwise \end{cases} \tag{4}$$

$$\lambda_{i,G+1} = \begin{cases} \lambda_l + rand_3 * \lambda_u, & if \quad rand_4 < 0.1 \\ \lambda_{i,G+1}, & otherwise \end{cases} \tag{5}$$

$$CR_{i,G+1} = \begin{cases} rand_5, & if \quad rand_6 < 0.1 \\ CR_{i,G+1}, & otherwise \end{cases} \tag{6}$$

where *rand1*, *rand2*, *rand3*, *rand4*, *rand5* and *rand6* are uni form random numbers with thin values uniformly between 0 and 1. And F_l, F_u, λ_l and λ_u are the lower and the upper limits of F and λ, respectively .Both F_l and λ_l are set to 0.1 and both F_u and λ_u are set to 0.9.

Based on the self-adaptive concept, the F, λ and CR parameters adjust automatically while the time complexity does not increase. More details about the SADDE algorithm can be found in [18]. It should be noted that the value of Fourier series used to describe the shape of the cylinder will be determined by the DDE and SADDE scheme.

5 NUMERICAL RESULT

As shown in Figure 1, the problem space is divided in 68×68 grids with the grid size $\Delta x = \Delta y = 5.95$ mm. The dielectric cylinder is buried in lossless slab medium ($\sigma_1 = \sigma_2 = \sigma_3 = 0$). The transmitters and receivers are placed in free space above the homogeneous dielectric. The permittivities in region 1, region 2 and region 3 are characterized by $\varepsilon_1 = \varepsilon_0$, $\varepsilon_2 = 6\varepsilon_0$ and $\varepsilon_3 = \varepsilon_0$, respectively, while the permeability μ_0 is used for each region, i.e., only non-magnetic media are concerned here.

The scatterer is illuminated by plane waves with the electric field polarized along the axis, while the time dependence of the field is of a one derivative Gaussian pulse. The cylindrical object is illuminated by a transmitter at two different positions, N_i=2, which are located at the (-143mm, 178.5mm) and (143mm, 178.5mm), respectively. The scattered E fields for each illumination are collected at the eight receivers, *M*=8, which are equally separated by 47.8mm along the distance of 48mm from the interface between region 1 and region 2.

For the example, the dielectric cylinder with shape function $F(\theta) = 29.75 + 5.95\cos(4\theta)$ mm and the relative permittivity of the object is $\varepsilon_r = 3.5$ is considered. The final reconstructed shapes by SADDE and DDE at the 300 th generation are compared to the exact shape in Figure 2. The r.m.s. error of shape function for SADDE and DDE are about 2.31% and 2.51% in the final generation, respectively. The relative error for permittivity by SADDE and DDE are both less than 1%.The R.M.S. error of the reconstructed shape $F^{cal}(\theta)$ and the relative error for permittity with respect to the exact values versus generations are shown in Figure 3. It is clear that the SADDE a little bit outperforms DDE for this example.

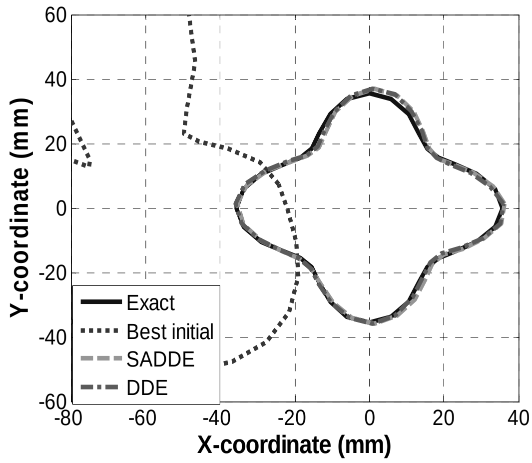

Fig. 2. The reconstructed shapes of the cylinder for example by DDE and SADDE, respectively.

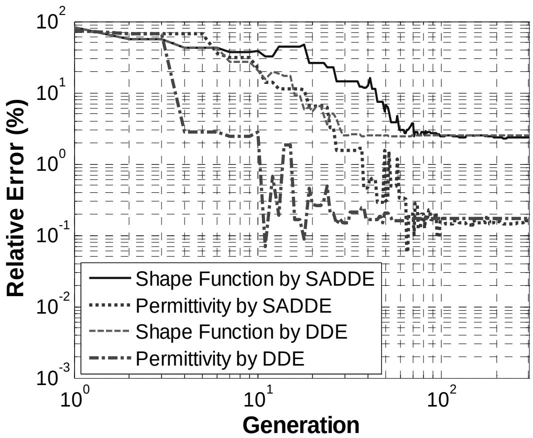

Fig. 3. Error value versus generation for example by DDE and SADDE, respectively.

6 CONCLUSION

In this paper, we study the time domain inverse scattering of an arbitrary cross section dielectric cylinder. Numerical results show that result by SADDE in accurate reconstruction. Finally, SADDE leads to more precise reconstruction results for the same population size and total number of iterations. It should be mentioned that this comparative study is indicative and its conclusion should not be considered generally applicable in all inverse scattering problems.

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