Application of FDTD and Dynamic Differential Evolution for Inverse Scattering Problem

Time domain inverse scattering

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***Abstract*—This paper reports a two-dimensional time-domain inverse scattering algorithm based upon the finite-difference time domain method for determining the shape of a perfectly conducting cylinder. Finite difference time domain method (FDTD) is used to solve the scattering electromagnetic wave of a perfectly conducting cylinder. The inverse problem is resolved by an optimization approach and the global searching scheme dynamic differential evolution (DDE) is then employed to search the parameter space. By properly processing the scattered field, some electromagnetic (EM) properties can be reconstructed. A set of representative numerical results is presented to demonstrate that the proposed approach is able to efficiently reconstruct the electromagnetic properties of metallic scatterer even when the initial guess is far away from the exact one.**

Keywords- Inverse Scattering, FDTD, Asynchronous particle swarm optimization (APSO), Cubic-Spline.

I. INTRODUCTION

Numerical inverse scattering studies found in the literature are based on either frequency or time domain approaches. Time domain approaches can exploit causality to limit the region of inversion, potentially reducing the number of unknowns. Time-domain inverse-scattering problems somewhat related to the present study commonly appear in the area of geosciences and remote sensing [1]–[2]. The scatterer reconstruction belongs to the general category of limited angle microwave imaging problems. These problems are both nonlinear and ill-posed [3]. The ill-posedness is often a mathematical characteristic of inverse problems. In general, the ill-posedness can be treated by traditional regularization schemes or transformed into a better condition problem [4]. In the latter possibility a type of regularization is also inherent.

In general, the nonlinearity of the problem is coped with by applying iterative optimization techniques [5]-[6]. Those algorithms based on stochastic strategies, offer advantages relative to local inversion algorithms including strong search ability simplicity, robustness, and insensitivity to ill-posedness. Some population-based stochastic methods, such as genetic algorithm (GA) [7], differential evolution (DE) [8], particle swarm optimization (PSO) [8]-[9] are proposed to search the global extreme of the inverse problems to overcome the drawback of the deterministic methods. To the best of our knowledge, there is still no investigation using the DDE to reconstruct the electromagnetic imaging of perfectly conducting cylinder with arbitrary shape in free space under time domain.

In this paper, the computational methods combining the FDTD method [10] and the DDE algorithm is presented. The forward problem is solved by the FDTD method, for which the subgridding technique is implemented to closely describe the fine structure of the cylinder. 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 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 dynamic differential evolution 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.

II. FORWARD PROBLEM

Let us consider a two-dimensional metallic cylinder in a free space 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.

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

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

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 [11].

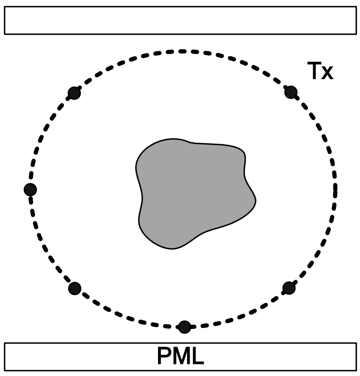

Fig. 1. Geometrical configuration of the problem.

III. 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 is employed to minimize the following objective function (OF):

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

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.

IV. Dynamic Differential Evolution

DDE algorithm starts with an initial population of potential solutions that is composed by a group of randomly generated individuals which represents shape function 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 $\{x_i: \ i=1,2,\cdots,Np\}$, 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 key distinction between a DDE algorithm and a typical DE is on the population updating mechanism. In a typical DE, all the update actions of the population are performed at the end of the generation, of which the implementation is referred as static updating mechanism. Alternatively, the updating mechanism of a DDE algorithm is carried out in a dynamic way: each parent individual will be replaced by his offspring if the offspring has a better objective function value than its parent individual does. Thus, DDE algorithm can respond the progress of population status immediately and to yield faster convergence speed than the typical DE. Based on the convergent characteristic of DDE algorithm, we are able to reduce the numbers of objective function evaluation and reconstruct the microwave image efficiently.

V. NUMERICAL RESULT

In this section, we report some numerical results using the method described in Section II. 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 metallic cylinder is located in free space. The cylindrical object is illuminated by a transmitter at four different positions, N_i=4. The scattered E fields for each illumination are collected at the eight receivers, M=8. Note that the simulated result using one incident wave is much worse than that by two incident waves. In order to get an accurate result, four transmitters are used here. The transmitters and receivers are collocated at a distance of 24 grids from the origin. The incident current pulse $I_z(t)$ is expressed as:

$$I_z(t)=\begin{cases}Ae^{-\alpha(t-\beta\Delta t)^2} & ,t\le T_w\\ 0 & ,t>T_w\end{cases} \tag{3}$$

where $\beta = 24$, $A = 1000$, $\Delta t = 13.34\text{ps}$, $T_w = 2\beta\Delta t$, and

$$\alpha = \left(\frac{1}{4\beta\Delta t}\right)^2$$

The time duration is set to $250\,\Delta t$ ($Q = 250$). Note that in order to accurately describe the shape of the cylinder, the subgridding FDTD technique is used both in the forward scattering (1:9) and the inverse scattering (1:5) parts – but with different scaling ratios as indicated in the parentheses. For the forward scattering, the E fields generated by the FDTD with fine subgrids are used to mimic the experimental data in (2).

There are eleven unknown parameters to retrieve, the radius ρ_i, $i = 1,2,\cdots,8$ of the shape function of the object and the center position of the cylinder plus the slope ρ'_N. Very wide searching ranges are used for the modified DDE to optimize the objective function given by (2). The parameters and the corresponding searching ranges are listed follow: $-47.6\text{mm} \le X_O \le 47.6\text{mm}$, $-47.6\text{mm} \le Y_O \le 47.6\text{mm}$, $5.95\text{mm} \le \rho_i \le 71.4\text{mm}$, $i = 1,2,\cdots,8$. The relative coefficients of the modified DDE are set as below: The operational coefficients are set as below: The crossover rate *CR* is set to be 0.8. Both parameters F and λ are set to be 0.8. The population size *Np* is set to be 110.

The reconstructed images for the relative error of the third example are shown in Fig 2. The shape function of this object is given by $F(\theta) = 29.75 + 5.95\cos(3\theta) + 5.95\sin(2\theta)$ mm. Figure 3 shows that the relative errors of the shape decrease quickly and good convergences are achieved within 30 generation. The r.m.s. error DF is about 2.8% in the final generation.

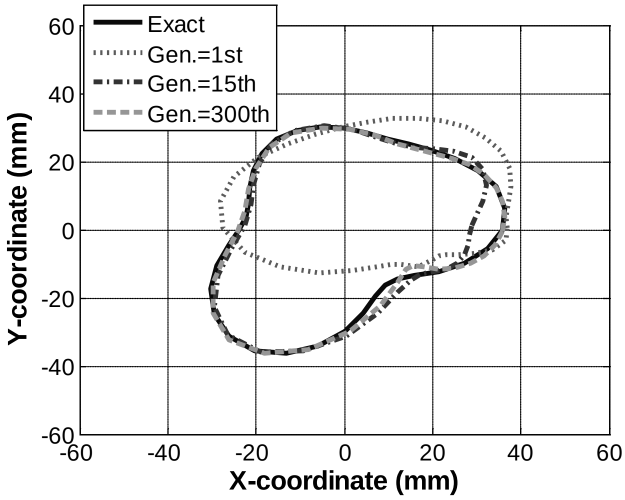

Fig. 2. The reconstructed cross section of the cylinder of the example at different generations.

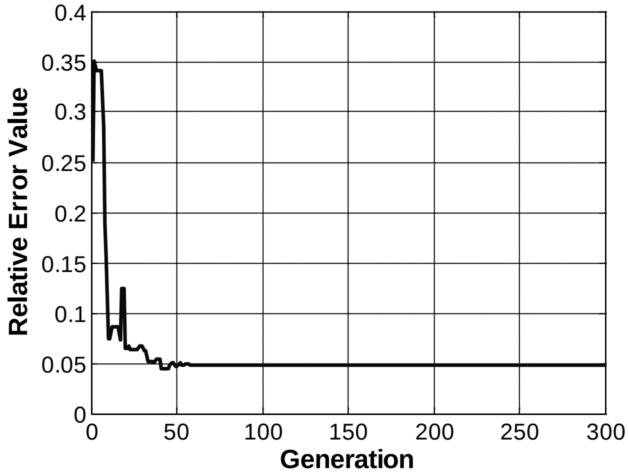

Fig. 3. Shape function error versus generation for the example.

VI. INVERSE PROBLEM

In this paper, we study the time domain inverse scattering of an arbitrary cross section metallic cylinder in free space. By combining the FDTD method and the DDE, good reconstructed results are obtained. The inverse problem is reformulated into an optimization one, and then the global searching scheme DDE is employed to search the parameter space. By using the DDE, the shape of the object can be successfully reconstructed.

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