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Microwave imaging of dielectric cylinders from experimental scattering data based on the genetic algorithms, neural networks and a hybrid micro genetic algorithm with conjugate gradient

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ABSTRACT

The application of three techniques for the reconstruction of the permittivity profile of cylindrical objects from scattered field measurements is studied in the present paper. These approaches are applied to two-dimensional configurations. After an integral formulation, a discretization using the method of moments (MoM) is applied. Considering that the microwave imaging is recast as a nonlinear optimization problem, a cost functional is defined by the norm of a difference between the measured scattered electric field and that calculated for an estimated relative permittivity distribution. Thus, the permittivity profile can be obtained by minimizing the cost functional. In order to solve this inverse scattering problem, three techniques are employed. The first is based on a basic real coded genetic algorithms (GAs). The second is a hybrid technique (mGA-CG) which is based on a conjunction of a micro genetic algorithm (mGA) approach with the conjugate gradient based method (CG). The third is an application of an artificial neural network (ANN) having multilayered perceptrons architecture (MLPs). Three algorithms: conjugate gradient with Polak–Ribiere updates (CGP), Levenberg–Marquardt (LM) and gradient descent (GD) are used to train the ANN. Computer simulations of these methods are performed for reconstruction of circular cylinders against laboratory-controlled microwave data.

1. Introduction

The electromagnetic imaging of material parameters of unknown objects remains one of the most interesting and important topics due to its practical applications such as, detection of buried objects [1], non-destructive evaluation of materials [2], and biomedical diagnostics [3–5], etc. In microwave imaging, the objective is to characterize an unknown object by its complex permittivity from measurements of the scattered field which results when a known incident wave interacts with the object. The wave-object interaction can be described by two contrast-source integral equations which link the resulting scattered and total fields to a contrast (or object) function representative of the complex permittivity. Electromagnetic inverse problems are characterized by their nonlinearity and ill-posedness [6]. By ill-posedness (in the sense of Hadamard) it is meant that one of the following conditions is not satisfied: (i) the existence of the solution; (ii) the uniqueness of the solution; or (iii) the continuity of the inverse mapping. Over the past decades, significant progress has been made in the development of reconstruction algorithms. The diffraction tomographic algorithms have been developed to solve the inverse scattering problem. The formulations are based on the Born approximation in which the total field within the object is approximately equal to the incident field [7,8]. The limitations of diffraction tomography moreover stimulated the development of iterative methods and stochastic approaches. Many deterministic algorithms are applied for electromagnetic inverse scattering problem such as, the Newton–Kantorovich method [9,10], modified gradient method [11] and distorted Born iterative method [12]. These methods represent the microwave imaging as a nonlinear optimization problem. The final permittivity profile is computed iteratively. Indeed, during each iteration, the measured scattered field is compared with the scattered field computed from the numerical model. Then, these parameters profiles are progressively adjusted by minimizing the error between the two data sets. The major problem of these methods is due to the requirement of an accurate initial estimate profile for the object. To overcome these difficulties, others approaches based on stochastic methods were applied in microwave imaging. A microwave imaging of buried objects using genetic algorithms (GAs) approaches and the particle swarm optimization for the reconstruction of microwave images are given in [13,14], respectively. In the present paper, we provide a hybrid technique mGA-CG which a micro genetic

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algorithm (mGA) approach is combined with the conjugate gradient method (CG). The objective of this method is to accelerate the estimation of relative permittivity profile of a dielectric cylinder embedded in free space. Another method based on artificial neural networks (ANNs) was tested for the detection and localization of the same object. ANN has been widely used in microwave engineering [15,16]. In our case, measurements of the scattered field at the observation points and the permittivity of the object domain represent the inputs and outputs of the network, respectively. Compared with GA and mGA-CG methods, the principal advantage of the neural networks is that no formulation of the direct problem is necessary. The object is illuminated by a transverse magnetic (TM) polarized plane wave, samples of the scattered field are obtained on a circle in the surrounding domain and scatterer cross section is assumed to be included in a fixed test area.

2. Forward problem formulation

Let us consider two-dimensional (2-D) geometry as shown in Fig. 1.

The object with cross section Ω which is infinitely long (along the z-axis of a cartesian coordinate system) is assumed to be located in free space medium of dielectric permittivity ε_0. The material property of the object is characterized by the relative complex permittivity (RCP) $\varepsilon_{r,\Omega}(x,y)$ which vary only with respect to the transverse coordinates (x and y axis). The object is also considered nonmagnetic that its magnetic permeability be equal everywhere to μ_0. It is pointed out that $\varepsilon_{r,\Omega}(x,y)$ is given by the following expression:

$$\varepsilon_{r,\Omega}(x,y)=\varepsilon_r'(x,y)+\mathrm{j}\,\frac{\sigma(x,y)}{\omega\varepsilon_0}, \tag{1}$$

where ω denotes the angular frequency of the incident field. The object domain is illuminated by a TM incident plane wave (since the incident electric field is polarized in the z-axis, $\vec{E}_{inc}=E_{inc}\vec{\mathbf{z}}$). The incident electric field is given as follows:

$$E_{inc}(x,y)=\exp(-K_0(x\cos\varphi_{inc}+y\sin\varphi_{inc})), \tag{2}$$

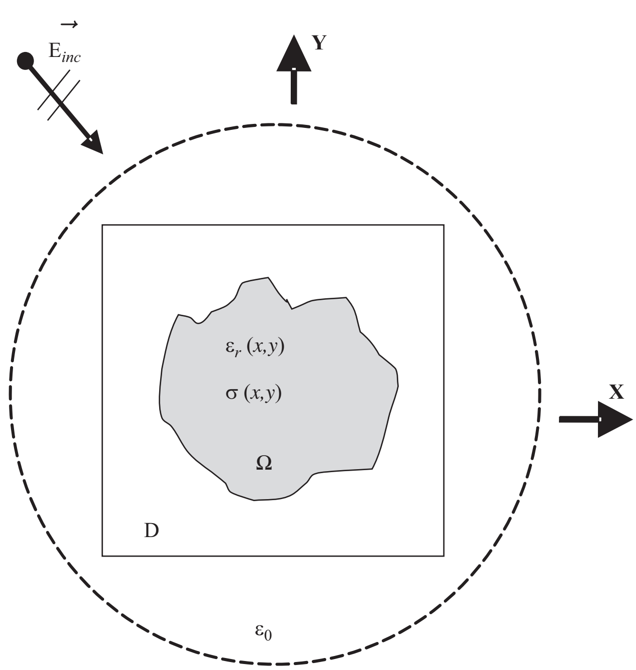

Fig. 1. Geometric configuration of the 2-D scattering problem.

φ_{inc} and $K_0=\omega\sqrt{\varepsilon_0\mu_0}$ denote the incidence angle and the wave number of the free space, respectively.

Thus the scattering problem can be reduced to two dimensional. The scattered and total electric fields $\vec{E}_s=E_s\vec{\mathbf{z}}$ and $\vec{E}=E\vec{\mathbf{z}}$, respectively, are also parallel to the z-axis considering the scalar nature of the problem. The time dependency has the $\exp(-\mathrm{j}\omega t)$ form. The total electric field represents a solution of the Helmoltz wave equation below:

$$\nabla^2E(x,y)+K_0^2\varepsilon_r(x,y)E(x,y)=0. \tag{3}$$

In Eq. (3), $\varepsilon_r(x,y)$ denotes the relative complex permittivity distribution in all space:

$$\varepsilon_r(x,y)=\begin{cases}\varepsilon_{r,\Omega}(x,y), & (x,y)\in D,\\ 1, & (x,y)\notin D.\end{cases} \tag{4}$$

The forward problem consists of computing the scattered field from the knowledge of permittivity profile and a particular incident field. While, the tomographic imaging objective is to determine an unknown permittivity distribution from the measured scattered fields (data) for a given incident field. Let us use this equality: $\vec{E}=\vec{E}_{inc}+\vec{E}_s$, then the scattered electric field $\vec{E}_s$ can be defined as a solution of the following reduced equation:

$$\nabla^2E_s(x,y)+K_0^2E_s(x,y)=-K_0^2C(x,y)E(x,y), \tag{5}$$

where $C(x,y)=(\varepsilon_r(x,y)-1)$ denotes the contrast function. Under these assumptions, when the object is illuminated by a set of V TM incident fields, the total electric field $E^\nu(x,y)$, $\nu=1,\ldots,V$, satisfies the following integral equation, which is also called the "state equation":

$$E^\nu(x,y)=E^\nu_{inc}(x,y)+K_0^2\iint_D g(x,y,x',y')C(x',y')E^\nu(x',y')\,dx'\,dy'(x,y)\in D. \tag{6}$$

In (6), $g(x,y,x',y')$ is the Green's function in two dimensions given by: $g(x,y,x',y')=(\mathrm{j}/4)H_0^{(1)}(K_0\sqrt{(x-x')^2+(y-y')^2})$, which $H_0^{(1)}$ is the Hankel function of the second kind and zero order. The measurement domain S is formed by an arrangement of probing antennas located at M positions (x_m,y_m), $m=1,\ldots,M$, and surrounding the object domain D. For each excitation of index ν, the scattered electric field $E_s^\nu(x_m,y_m)$ satisfies the following relation representing the "data equation":

$$E_s^\nu(x_m,y_m)=K_0^2\iint_D g(x_m,y_m,x',y')C(x',y')E^\nu(x',y')\,dx'\,dy'(x_m,y_m)\in S. \tag{7}$$

In order to treat the problem numerically, the first step is the discretization of (6) and (7). Thus, we consider a square investigation domain D subdivided into N square cells. In the n-th cell, the total field and dielectric permittivity are considered constant and equal to the corresponding value of the cell center denoted by its coordinates (x_n,y_n). In numerical practice, discrete versions of the above equations are considered. They are obtained by means the method of moments (MoM) with pulse-basis and point matching, which results in partitioning the test domain D into elementary pixels, small enough in order to consider the fields and the contrast as constant over each of them. Then (6) and (7) can be transformed into matrix equations as follows:

$$E_{inc}=(I-G_DC)E, \tag{8}$$

$$E_s=G_sCE, \tag{9}$$

where E and E_{inc} are $N\times V$ matrices, their ν-th columns vectors represent the N elements of the total and incident fields, respectively, on the test domain D correspond to the ν-th