Hybrid method for full identification of buried objects and surrounding media

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***Abstract*— This study describes a hybrid technique for identification of buried objects. The object's shape and electromagnetic profile are reconstructed from evaluations of electrical permittivity and conductivity. The method suggests a combination of linear sampling and optimization. Linear sampling method (LSM) is used to recover shape and metaheuristic optimizations essential to reconstruct the inside profile. A special case of a non-homogenous object is considered. In this case the object is a buried homogenous dielectric for which the position and volume of the hole inside is not known. In this case, after recovering data by the same process used in the first step, it is necessary to recover the volume and position of the hole. This case will be useful when the final target of identification is an embedded object. The final results of this case verify the effectiveness and feasibility of the proposed method. Effectiveness of the method is validated by application of one real world cases involving civil engineering. In all cases presented in this study, the rates of final reconstruction error are acceptable and less than 10%. These results prove that this proposed procedure can be applied to reconstruct hollow objects correctly.**

***Index Terms*—**Inverse scattering, linear sampling method, Optimization, Profile reconstruction.

I. INTRODUCTION

Imaging is a common technique used to identify unknown objects using electromagnetic waves. Specifications for imaging are dependent on the intrinsic properties of the applied wave. Different parts of the electromagnetic spectrum have different characteristics, and the nature of a wave affects the resulting image. Imaging in the visual part of an electromagnetic spectrum only reflects data relating to the surface of an obstacle. Visual light only reveals specification related to the outer surface features of an object such as shape and color. In order to gather data about properties related to the inside of an obstacle, it is necessary to manipulate other parts of the electromagnetic spectrum in order to identify non-visual properties of objects. Non-visual properties could be any parameter

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related to intrinsic properties of media such as its electromagnetic profile, or physical properties that cannot be seen from the outside such as a buried object inside the obstacle. Microwave imaging is a technique that uses data extracted from a scatterer in order to reconstruct its properties [1-3]. This technique has different names in different applications. It is called inverse scattering, profile identification, profile reconstruction, object identification and non-destructive testing [4]. These methods make it possible to retrieve comprehensive properties (geometrical and physical) of an object such as size, position, shape, electrical permittivity and conductivity. In general terms, the objectives of identification can be categorized in to three main groups as follows [5-7]:

1- Localization

2- Shape recovery

3- Profile extraction

The final objective for all types of inverse scattering problems could be expressed by a combination of these three main targets. For achieving each objective, several methods have been proposed. A novel approach is to combine 2 methods to achieve a combinational target. Some combinational methods have been proposed in recent years [8]. The proposal in this study applies a combination of two types of inverse method: linear sampling method, which can retrieve the outer shape and location, and optimization, which can extract the dielectric profile for two dimensional structures. The proposed optimization is that of particle swarm optimization (PSO). This combination of two methods enables a complete reconstruction of the outer shape and inside profile of a dielectric with any asymmetric shape. In addition, based on these results, it is possible to recover the shape of a buried object by this method. By means of this technique, it is possible to extract the shape of a hole inside an object. A full description of the technique is presented in the next sections.

II. DESCRPTION OF PROPOSED TECHNIQUE

According to different previous studies in inverse scattering, it is possible to retrieve the properties of a homogenous object based on two step procedure : the first step is based on far-field pattern data, in which linear sampling method recovers the outer contour of an object. This contour, which is considered as one of the final objectives, acts as input data for the second step. In the second step, optimization procedure is used in order to recover the profile of homogenous media with the shape known from first step. Our suggestion is to modify the second step in order to retrieve the inside shape of a buried object inside another object. The inside object's profile could be free space which means there is a hole inside the outer body and this means that the method could reconstruct a hole inside an object which could be named as a hollow object. In this case, it is supposed that the object is homogenous and that there is an unknown hole inside it. The profile of the hole is equal to the profile of free space. This kind of problem is defined according to several practical usages of inverse scattering. Whenever inverse scattering is applied to recover a buried object, usually the electrical profile of buried and outer media is known. In this case, recovery of the position and shape of the buried object is recommended. This proposed procedure is based on this type of application. The next step is improvement of buried object recovery. The procedure is applied to a practical case: extract data about rebar in concrete. In the sections below, our shape and profile recovering methods are described, and then the numerical results are presented. In this study, in order to calculate scattered far field pattern, Finite Difference Time Domain method (FDTD) is used [9]. FDTD is applied to solve Maxwell equation for our problem. The cell sizes (Δx and Δy) are determined in according to main body size to have a good accuracy. Simulations are done for TM polarization.

III. LINEAR SAMPLING METHOD

Linear sampling method, among other qualitative inverse scattering methods is fascinating [4,5]. The linear sampling method, as it is apparent in its name, samples the under test region and for each sample point, solves an integral equation. The answer of equation for each point is a function and it is called g_z [4-6]:

$$\int_{\Omega} u_{\infty}(\hat{x},d)\, g_z(d)\, ds(d) = \Phi_{\infty}(\hat{x},z) \tag{1}$$

In the (1), $\Phi_{\infty}(\hat{x},z)$ indicates far field pattern of a point source which is located at point z.. When g_z is computed for all of points in the under test area, the norm of g_z function acts the LSM indicator. In this point, it is essential to define a threshold value for LSM indicator, while for points inside the object, the value of the norm is lower than threshold and for points outside the object the index is higher than threshold. There are different suggestions for defining the value of threshold. Further detailed description is presented in references [10,11].

IV. OPTIMIZATION METHOD

In an effort to retrieve the profile of an under test object, a profile recovery method is needed. These kinds of methods are categorized in quantitative methods. Optimization methods are an important group of these methods. Stochastic optimizations are an efficient set for optimizing complicated problems. Unlike classical and some deterministic optimization, these methods have an important benefit; they can overcome local minima traps.

Several metaheuristic methods, inspired by natural phenomena are presented in this category. In this study one of these methods is used as the profile extractor: particle swarm intelligence (PSO).
PSO is verified as a quite efficient method for optimizing. A brief description of this method is introduced in the next section.

A. Particle swarm intelligence

In PSO, each candidate solution x_k is considered as a particle and has a velocity, v_k, used to move around the solution space. In particular, the particle is given a new position by [12,13]:

$$x_k(t+1)=x_k(t)+v_k(t) \quad (2)$$

While components of the velocity vector are updated according to the scheme:

$$v_k=\omega v_k+c_1q_1(x_{kn}^{b}-x_{kn})+ c_2q_2(g_n-x_{kn}) \quad (3)$$

In (3), ω is inertia, c_1 is cognitive, and c_2 social parameter, q_1 and q_2 are random numbers uniformly distributed in [0, 1]. In addition, $x^b = [x^{b1}, x^{b2}, . . . , x^{bN}]$ is the best position ever visited by the kth particle, while $g = [g^1, g^2, . . . , g^N]$ is the global best position found by the whole population. Obviously, if the new particle position derived from above relation is a better fit than x^b, then the latter is updated. Furthermore, g_k is updated respectively. In our simulations the value of PSO parameters are set to: ω=0.7, c_1=c_2=0.6. The cost function which is going to be minimized in this study is the relative difference of electrical field for simulated object (E^{sim}) to exact scattered field (E^{meas}):

$$F=\frac{\sum_{i=1}^{I}\sum_{j=1}^{J}\left\|\vec{E}_{ij}^{sim}-\vec{E}_{ij}^{meas}\right\|^2}{\sum_{i=1}^{I}\sum_{j=1}^{J}\left\|\vec{E}_{ij}^{meas}\right\|^2}+\alpha R(\varepsilon,\sigma) \quad (4)$$

V- RECOVERY OF OUTER SHAPE

Based on the described theory, simulation results are now ready for presentation. By applying the far field pattern of the object to linear sampling method, outer contour of media is recovered. Main shapes and recovered ones are presented in Fig. 1. All of the values are normalized to λ_0. The solid line is original shape and dots represent the reconstructed shape.

As the results in Fig.1 demonstrate, different and non-symmetric shapes could be retrieved. In all of these cases, shape of outer border is reconstructed with acceptable error.

VI- RECOVERY OF HOLLOW MEDIA

In several practical applications, the main objective of a reconstruction problem is to identify an object inside another media. Usually in these cases, the electrical property (i.e relative permittivity and conductivity) of both inner and surrounding media are known. In these cases, a procedure is needed to determine the shape and especially the volume and location of a buried object. In these cases location and volume are more important than the exact shape. Here we are intended to present a procedure to determine the inside object based on the successful full identification experiences revealed in previous sections. The procedure is followed according to that described below:

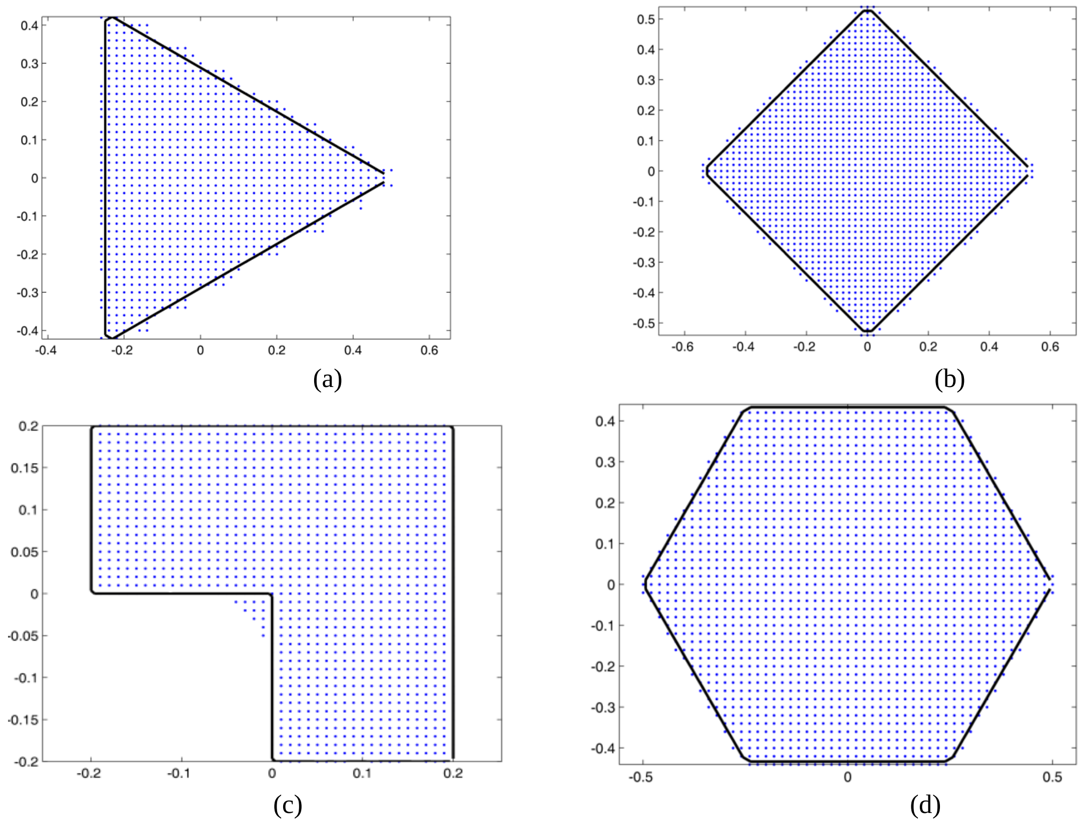

Fig. 1. Original and reconstructed shape (a) triangle (b) square (c) hexagon (d) incomplete square

The outer boundary of the object is known by LSM. Optimization procedure is applied in order to recover the buried object inside. The electrical property of the inner object is known and here we are going to recover its physical properties (i.e location and volume). These physical properties are used as optimization variables. In our procedure, first we approximate the cross section of inside embedded object with a circle with unknown location and radius. In this step the location and radius of circle are optimization variables. After finding these variables by optimization, in the second step we consider the embedded object by assuming the object as an unknown mass which is located in the place of circle but the shape can be arbitrary. In this step the area inside and outside nearby the circle is discretized to cells. In this step another optimization is carried out. In this phase of optimization, it is decided that whether the point is inside embedded mass or not. By optimizing the problem for second round, the optimization finds the contour of inner body.

Here we consider the problem in general form with typical values for size and electrical property and prove its validity. Different cases are considered in order to verify the procedure. The next section reports of the practical applications for this case using real values. In the tables, profile of surrounding media is (ε_{r1}, σ_1) and mass inside is (ε_{r2}, σ_2) .

Reconstruction models are done for different locations and sizes of the inside mass and various values of relative permittivity and conductivity. The final reconstruction errors are presented in Tables I,II.

Table I. RECONSTRUCTION ERROR FOR SHAPE OF FIG.1(a)

(ε_{r1},σ_1)	**(ε_{r2},σ_2)**	**Reconstruction error (%)**
(2.5,0.0)	(1,0.0)	9
(4,0.0)	(1,0.0)	8.9
(7,0.0)	(1,0.0)	8.3
(10,0.0)	(1,0.0)	8.3
(2,0.05)	(3,0.0)	9.1
(4,0.05)	(3,0.0)	9.0
(7,0.05)	(3,0.0)	8.9
(10,0.05)	(3,0.0)	8.8
(2,0.1)	(9,0.0)	8.5
(4,0.1)	(9,0.0)	8.6
(7,0.1)	(9,0.0)	8.9
(10,0.1)	(9,0.0)	9.5

Table II. RECONSTRUCTION ERROR FOR SHAPE OF FIG.1(c)

(ε_{r1},σ_1)	**(ε_{r2},σ_2)**	**Reconstruction error (%)**
(2,0.0)	(1,0.0)	8.2
(4,0.0)	(1,0.0)	7.9
(7,0.0)	(1,0.0)	7.7
(10,0.0)	(1,0.0)	6.9
(2,0.05)	(3,0.0)	8.5
(4,0.05)	(3,0.0)	8
(7,0.05)	(3,0.0)	7.9
(10,0.05)	(3,0.0)	7.2
(2,0.1)	(9,0.0)	7.4
(4,0.1)	(9,0.0)	7.9
(7,0.1)	(9,0.0)	8.1
(10,0.1)	(9,0.0)	8.5

Error is defined as described below: after reconstruction, comparisons are made between real cells and constructed cells, and the ratio of false reconstructed to number of cells in the whole mass is determined and defined as the reconstruction error. Results of reconstruction for 2 cases are depicted in Fig.2,3.

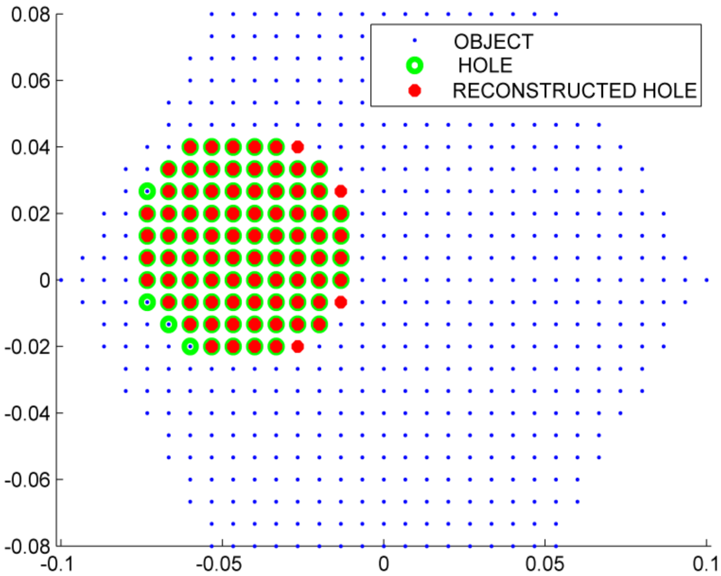

Fig. 2. Original and reconstructed shape for hexagon

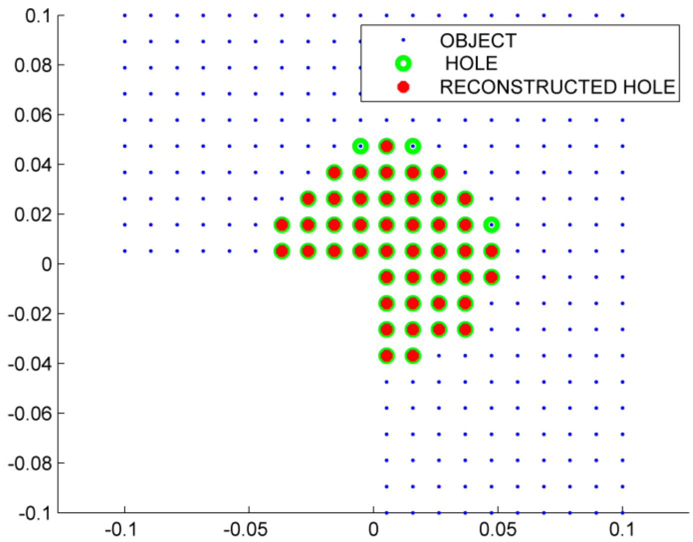

Fig. 3. Original and reconstructed shape for incomplete square

In addition, the problem is simulated for different locations of inside mass. Results reveal that reconstruction error is not highly sensitive to changes of location, but it is sensitive to size of inside mass. Finally, it can be concluded that the reconstruction error can verify effectiveness of this procedure. Up to this section values are selected typically and specific real-world values are not emphasized.

VII- PRACTICAL APPPLICATION FOR HOLLOW MEDIA RECOVERY

In practice, a common application of reconstruction is to recover the physical properties of a buried object, while the electrical properties of both outer and embedded bodies are known. In civil engineering, rebar steel bars are embedded inside the concrete to construct reinforced structures. In order to verify that the proper steel bars are used, a non-destructive means for testing is needed. Here again the electrical profile of both concrete and steel are known. The problem is recovery of the location and diameter of the bars. The mentioned practical usage is the same as cases that are considered in previous sections. The only difference is value of the electrical parameters. Here we simulate the problem for real values of this real-world application.

It is worthy to mention that according to practical cases which we focus on, our hybrid method is quite efficient. This arises from two conditions which we assume for our problem:

a. In our simulation the profiles of both inner and outer media are known.

b. The inhomogeneity inside the main body is not distributed and is a concentrated mass.

According to these two points, the number of parameters for optimizing decreases drastically and this point make the recovery time quite acceptable in comparision with general inhomogeneous object recovery using optimization. In reconstruction of an inhomogeneous media in general case, each cell have two variables (ε,σ) and the whole number of optimization variables are equal to two times the number of cells.

A. Reinforced rebar

A real world application for this procedure is in civil engineering. Civil engineers want to be sure about the rebar characteristic embedded inside concrete. The location and size of a steel bar inside has an important role that determines its performance in reinforced concrete. This procedure is applied in order to recover the size and location of a steel rebar embedded inside concrete. The inside matter is a steel bar, which is a conductor and the outer media is concrete.

Here, values of relative permittivity and conductivity are selected from practical studies. Actually, these values are variable as opposed to those of frequency. In this study these values are chosen according to results of a civil engineering study. These are mentioned below [14]: for concrete $(\varepsilon_{r1},\sigma_1)=(10,0.001)$ and rebar are conductors. Reconstruction errors for different scenarios are presented in Table III.

According to the results of Table III, it can be concluded that the procedure is efficient in civil engineering applications. It should be noted that for each scenario the simulation is repeated for different locations of buried mass and the average value of reconstruction error is mentioned in the Table III.

According to results mentioned in the Table, it can be concluded that the procedure presented in this study is efficient in civil engineering applications. In table III, R_2 represents rebar radius while R_1 is surrounding concrete radius. Reconstruction error versus iteration for one of cases is depicted in Fig.4. It should be noted that PSO is repeated for 250 times an each iteration means a repeat of PSO procedure.

Table III. RECONSTRUCTION ERROR FOR DIFFERENT VALUES OF R_2/R_1 FOR REBAR

R_2/R_1	Reconstruction error (%)
0.2	9.8
0.35	9.1
0.45	8.8

VIII- CONCLUSION

A hybrid method is proposed to identify the complete profile of a buried object based on scattering theory. The procedure includes two inverse methods: linear sampling and an optimization routine. A method is proposed to recover buried and hollow objects.

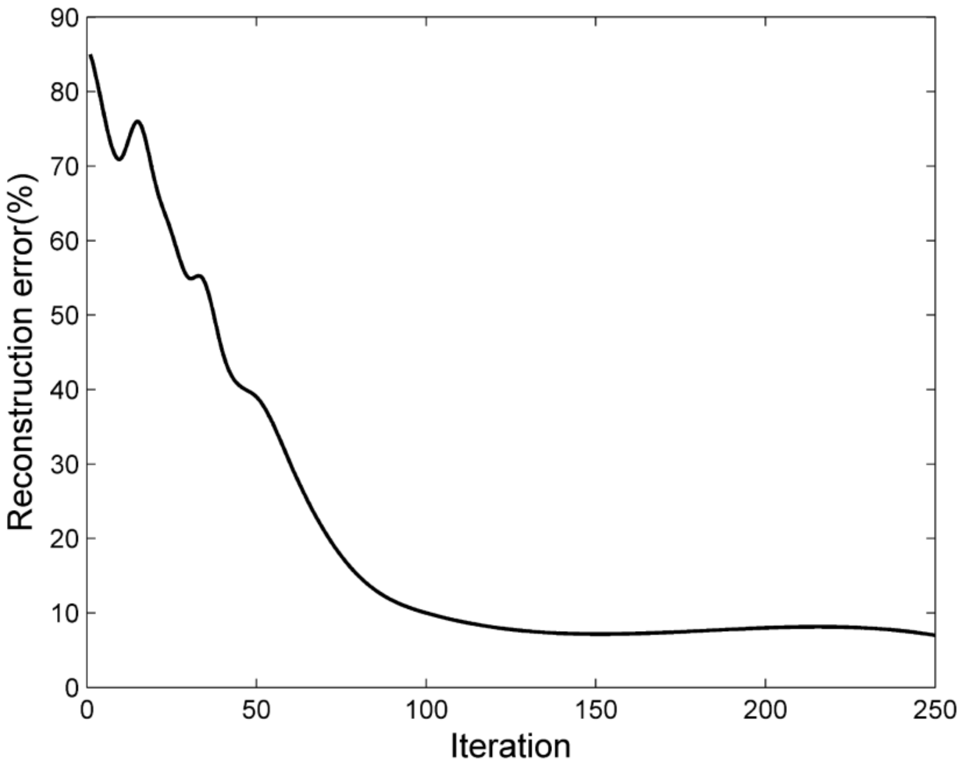

Fig. 4. Reconstruction error versus iteration for last case of rebar

To verify the method, the routine is tested for different profiles of outer and inner objects and different sizes of buried mass are used to verify the method. The reconstruction error validates the method. In the general form of hollow mass, the worst-case reconstruction error is less than 9 %. This indicates an acceptable recovery error. A practical application is introduced for this routine: reconstruction of the profile of steel rebar in concrete for civil engineering. In these cases, the procedure is repeated for real values of permittivity and conductivity based on measurements. Our final reconstruction errors prove that the procedure worked correctly in these real world cases and are appropriate for practical application. For civil engineering application, the results show reconstruction error of less than 10 percent. This value is quite satisfactory. In addition, although simulations are done for a real world usage, it should be noticed that it could be applied to several other practical cases such as finding oil reservoir.

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