Fast 3D microwave imaging inside cavity with minimum number of antennas and modified inverse algorithm

Omid Babazadeh

Abstract
This article proposes an optimized method for 3D microwave imaging of various unknown objects inside a perfect electric conductor cavity. The total field scattered field technique uses the finite difference time domain method to obtain scattered fields inside a cavity in the forward scattering problem. However, the conjugate gradient method is optimized and used alongside a combined regularization term in the inverse scattering problem, which is essential for the reconstruction process. A dipole antenna is located as an incident wave from the transmitting antenna. Besides, one antenna acts as the receiver. Identifying the unknown objects with different shapes, sizes, materials, and locations using the minimum number of transmitting and receiving antennas, and the newly developed algorithm with less computation time, are the main advantages of this article. Also, the implemented method can be used in the 3D microwave imaging of multi-scattering problems.

KEYWORDS
conjugate gradient, FDTD, forward scattering, inverse scattering, microwave imaging

JEL CLASSIFICATION
Electrical and electronic engineering

1 | INTRODUCTION

Microwave imaging is one of the most challenging and interesting applications of electromagnetic waves. It has been used to find the characteristics of the unknown object non-invasively. Microwave imaging inside the cavity helps to control the resonance frequency in detecting objects. Thus, it has been used in nondestructive testing and evaluation and medical imaging. Also, microwave imaging is helpful in concealed weapon detection at security checkpoints and through-the-wall imaging.

Generally, the mentioned problem consists of two main parts: (a) forward scattering problem and (b) inverse scattering problem. In the forward scattering problem, the aim is to find the scattered fields. Several well-known approaches have been introduced in the forward scattering problem like finite difference time domain (FDTD), total field scattered field (TFSF), finite difference frequency domain (FDFD), and method of moments (MOM). In the inverse scattering problem, the goal is to reconstruct the parameters of the unknown object. Mostly, the matrix form of the operators in
the inverse scattering problem is ill-posed in the Hadamard sense.\textsuperscript{11} However, to solve this problem, many linear and nonlinear methods have been introduced.

Inverse scattering problem can be solved using Born and Rytov approximation\textsuperscript{12,13} which are suitable for transparent objects, Born iterative method (BIM),\textsuperscript{14} distorted Born iterative method (DBIM),\textsuperscript{15} subspace-distorted Born iterative method (S-DBIM),\textsuperscript{16} genetic algorithms,\textsuperscript{17,18} singular value decomposition (SVD),\textsuperscript{19} contrast source inversion (CSI),\textsuperscript{20,21} source reconstruction method (SRM),\textsuperscript{22} stabilized bi-conjugate gradient method,\textsuperscript{23} fast Fourier transform (FFT),\textsuperscript{24} conjugate gradient (CG) method,\textsuperscript{25–27} non-iterative deep learning method,\textsuperscript{28} and LSTM based processing method.\textsuperscript{29} In the most reported works, some limitations in identifying the shape of objects arise, and it is because of the methods implemented in the imaging problem. For instance, elapsed time, reconstruction quality, imaging in a multi-layer medium, and imaging small objects are challenging concepts. In this article, the elapsed time is decreased, and the imaging quality is increased.

Microwave imaging inside a cavity is a novel and challenging concept. First, Green’s function should be implemented for the space inside the cavity, which is more complicated than Green’s function of free space. Besides, the quality of fabrication in the practical cases could be determinative in getting good reconstruction.

This article aims to do the quantitative and qualitative 3D reconstruction of unknown objects with various properties inside a cavity using only one transmitter and receiver antennas. However, if the space inside the cavity fills with a high permittivity material, the reconstruction will be only quantitative. The forward scattering problem is implemented using a well-known method. However, for the inverse scattering problem, a high error controllable algorithm is used to reconstruct different shapes of scatterers characterized by various sizes, locations, and permittivity.

2 | ANTENNA DESIGN

As it is mentioned, one transmitter and one receiver antennas are used in this article. Besides, an infinitesimal electric dipole antenna ($\ell = \lambda/50$) is used in designing receiver and transmitter. If the cavity locates in $-\frac{a}{2} \leq x \leq \frac{a}{2}$, $-\frac{b}{2} \leq y \leq \frac{b}{2}$, $-\frac{c}{2} \leq z \leq \frac{c}{2}$, then the position of transmitter and receiver antennas can be chosen as:\textsuperscript{30}

$$P_T(x, y, z) = \left(0, \frac{-b}{2} + 2\Delta y, 0\right),$$

$$P_R(x, y, z) = \left(0, \frac{b}{2} - 2\Delta y, 0\right).$$

(1)

Because the length of antenna is small comparing to wavelength, current distribution considered constant on the dipole. Electric and magnetic fields in this case for a dipole in $\hat{z}$ axis are expanded in the following way:

$$\vec{I}(\vec{z}) = I_0\hat{z}.$$  

(2)

Using magnetic vector potential ($\vec{A}$), we could find E-field and H-field directly. Also, to simplify the integral calculation, in solving $\vec{A}$, we could make the following modification:

$$|r - r'| \approx r, \quad \ell = \frac{\lambda}{50}.\quad (3)$$

Thus, we will have:

$$\vec{A}(\vec{r}) = \frac{\mu_0}{4\pi} \int \vec{I}(\vec{z'}) \frac{e^{-jkr}}{r} dz'.\quad (4)$$

As a reason, we will define E-field and H-field as the following:

$$\vec{H} = \frac{\nabla \times \vec{A}}{\mu_0\mu_r},$$

$$\vec{E} = -j\omega\vec{A} - j\frac{\nabla(\nabla \cdot \vec{A})}{\omega\varepsilon_0\mu_r\varepsilon_\infty\varepsilon_r}.\quad (5)$$
3 | FORWARD SCATTERING PROBLEM

In the forward scattering problem, the aim is to calculate 3D scattered fields. As it is shown in Figure 1, the imaging medium inside the cavity can be divided into two regions: region 1 (TF) containing the incident and scattered fields which are, in sum, the total field. Also, transmitting antennas are located at the boundary of this region. However, region 2 (SF), the space between the PEC cavity and region 1, contains only the scattered fields. Therefore, the implemented technique is called TFSF.

FDTD is one of the valuable methods in solving field equations inside the cavity. For this, the resonance frequency of the dominant mode for the cavity should be calculated as follows:

\[
 f_{mnlp} = \frac{u}{2} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{p}{c}\right)^2} \quad \text{(Hz)},
\]

where \(u\) is the speed of light; integers \(m\), \(n\), and \(p\) denote the number of the modes; and \(a\), \(b\), and \(c\) show the length of the cavity in \(x\), \(y\), and \(z\) directions, respectively.

In the FDTD solver, the imaging medium should be divided into small cubic boxes. In this case, the space in each axis is discretized into a few grids \(N_v\), where \(v\) shows the \(x\), \(y\), or \(z\)-axis, respectively. Thus, it will be defined by:

\[
 N_i = \frac{a}{\Delta i}, \quad i = x, y, z.
\]

\(\Delta x\), \(\Delta y\), and \(\Delta z\) are the length of the discretized boxes; since \(a = b = c\) then \(N_x = N_y = N_z = N\). The incident field will be added to the border of the two separated regions to satisfy the TFSF condition.

\(E_0\) is the amplitude of the incident wave and \(\vec{k}\) is the wave vector. After updating the electric and magnetic fields, the incident field must be added and subtracted from the border components concerning the location of the incident plane waves to bring about the TFSF boundary condition. For instance, the updating procedure of the \(x\) component will be as:

\[
 E_x = E_x \pm \left(\frac{\Delta t}{\varepsilon_0 \Delta y}\right) H_z^{inc},
\]

\[
 H_x = H_x \pm \left(\frac{\Delta t}{\mu_0 \Delta y}\right) E_z^{inc},
\]

\[
 E_x = E_x \pm \left(\frac{\Delta t}{\mu_0 \Delta z}\right) H_y^{inc},
\]

\[
 H_x = H_x \pm \left(\frac{\Delta t}{\varepsilon_0 \Delta z}\right) E_y^{inc}.
\]

\(E_w^{inc}\) and \(H_w^{inc}\) are the \(w\) components of the incident fields.

**Figure 1** Structure of imaging medium, region 1 (TF) in green color and region 2 (SF) in yellow color.
Besides, the boundary condition for the PEC cavity should be satisfied. In this case, tangential components of the electric field should be zero in each boundary. For instance, at \( x = 0 \), the boundary condition is considered as:

\[
\begin{align*}
E_y(0,y,z) &= 0, \\
E_z(0,y,z) &= 0.
\end{align*}
\] (10)

4 | INVERSE SCATTERING PROBLEM

First, to reconstruct the unknown object using obtained scattered fields, Green’s function should be solved inside the cavity. Considering the lossy medium, Green’s function inside the cavity will be the same as Green’s function of the free space since it absorbs scattered waves from the cavity walls. However, it is crucial to pick the optimized value for the loss of medium. In this article, the value is chosen by comparing the error in reconstruction for different cases. As a reason, the scalar Helmholtz equation is written as follows:

\[\nabla^2 G(r,r') + k_0^2 G(r,r') = -\delta(r-r').\] (11)

where \( k_0 \) is wave number in free space. By solving (11), scalar Green’s function can be as:

\[G(r,r') = \frac{j}{4} H_0^{(1)} \left( k_0 \left| \vec{r} - \vec{r}' \right| \right).\] (12)

Equation (12) expresses the Green’s function in a homogeneous medium. \( H_0^{(1)} \) is the Hankel function of zeroth order and first kind, and \( \left| \vec{r} - \vec{r}' \right| \) is the distance between the observation and source points. Total field can be defined by:

\[\vec{E}^T = \vec{E}^{\text{sea}} + \vec{E}^{\text{inc}}.\] (13)

Using scalar Helmholtz formula in (11), Equation (13) can be rewritten in the following way:

\[
\begin{align*}
\vec{E}^T(x,y,z) &= \vec{E}^{\text{inc}}(x,y,z) \\
&+ \int \int_s G(r-r') k_0^2 \left( \epsilon_r(x',y',z) - \epsilon_m \right) \\
&\times \vec{E}^T(x',y',z) \, dx' \, dy',
\end{align*}
\] (14)

where \( s \) is the cross-section of the scatterer object, \( \epsilon_r \) and \( \epsilon_m \) are the permittivity of the object and medium, respectively. Furthermore, we can organize (14) in a suitable way to rewrite it as a linear matrix equation. Thus, the linear system will be defined by:

\[X = \frac{\epsilon_r(x',y',z_0) - \epsilon_m}{\epsilon_m},\] (15)

\[A = k_0^2 \int \int_s G(r-r') \vec{E}^T(x',y',z_0) \, dx' \, dy'.\] (16)

Considering (13), (15), and (16), the nonlinear integral in (14) can be rewritten as the linear matrix equation in the following way:

\[[A][X] = [b].\] (17)

\([A]\) is the matrix of operators, \([X]\) is the unknown coefficients, and \([b]\) expresses the calculated fields. The most significant point in solving the inverse scattering problem is that the inverse of the \( A \) matrix is ill-posed.
inverse algorithm is used to overcome the ill-posed condition. The algorithm is based on the CG algorithm and a combined regularization term. In that case, the cost function for this problem is expanded in two different forms for odd and even cases, and it could be written as follows:

\[
C = \begin{cases} 
\frac{|||b||^2 - |AX||^2||}{||b||^2}, & N = 0, 2, \ldots, \\
||A' \times b||, & N = 1, 3, \ldots . 
\end{cases}
\] (18)

For even cases, the relative error is considered, which controls the error in a meaningful range. Besides, the new type of cost function is written for the odd case, which is a simplified form of even case, and it helps to do the reconstruction faster. It should be mentioned that the forward scattering problem is essential in implementing the combined regularization term. As a result, the combination of implementations for even and odd cases gives the accuracy and speed to the inverse scattering problem, respectively.

In the CG method, an initial guess for the unknown parameter should be made. Whenever the obtained value for the unknown parameter satisfies the condition of the algorithm, the reconstruction process could be done.

\[X_{i+1} = X_i + \alpha_i d_i.\] (19)

In (19), \(\alpha_i\) is the step length where \(d_i\) is the search direction. Search direction could be calculated using Polak–Ribiére weighting. Thus, it is defined by:

\[d_i = g_i + P_i d_{i-1},\] (20)

\[P_i = \frac{g_i^2 \left( g_i - g_{i-1} \right)}{||g_{i-1}||^2}.\] (21)

The algorithm in this article is processed in parallel mode and optimized in implementation to approximate the exact value of an unknown object using a few iterations with a less convergence error and computation time.

5 | NUMERICAL RESULTS

Various examples are considered here to validate the method. All investigations are done inside a cavity with the features same as Figure 1. The resonant frequency of the cavity for the chosen length in each dimension is 1.675892 GHz.

5.1 | Spherical and cubic scatterers

The first example is reconstructing a single sphere and a single cube characterized by \(\epsilon_r = 4\) inside a cavity. The cavity is a cube with \(a = b = c = 20\) cm and is characterized by \(\epsilon_m = 1.2\) and \(\sigma = 0.5\).

\[\text{FIGURE 2} \quad \text{(A) Spherical and (B) cubic scatterers}\]
FIGURE 3  Reconstruction in two different mesh grids with same features for spherical scatterer (A) $N = 86$ and (B) $N = 148$

FIGURE 4  Reconstruction in two different mesh grids with same features for cubic scatterer (A) $N = 86$ and (B) $N = 148$
The imaging in this example is done in two different mesh grids as \( N = 86 \) and \( N = 148 \). Figure 2 shows the spherical and cubic scatterers characterized by \( r = 3 \) cm and the length of 3 cm in each dimension, respectively.

Also, Figures 3 and 4 demonstrate the 3D reconstruction of spherical and cubic scatterers in two different mesh grids, respectively. As it is clear, by increasing the number of mesh grids, the imaging quality becomes better.

5.2 Microwave imaging of multi scatterers

In this example, two cubic and spherical scatterers are placed inside the cavity in different locations. The size of the scatterers is different, where the length of the small cube is 8 mm on each axis, and the larger cube has a length of 12 mm. The spherical scatterers will have a radius of 8 and 12 mm.
The example is solved for $N = 202$ mesh grids. Moreover, the permittivity of the spherical scatterers is $\varepsilon_r = 4$. However, it is assumed $\varepsilon_r = 8$ for the cubic scatterers. Furthermore, the medium feature in this example is the same as the previous example. Figure 5 demonstrates the scatterers inside the cavity, and Figure 6 shows the 3D reconstruction of the scatterers in two different mesh grids.

To show the minimum distance between scatterers in the multi-scattering problem, the distance is reduced to 1 mm and shown in Figure 7. The reconstruction is done with a good result for the low distance between the scatterers. However, it is done with more mesh grids ($N = 148$) and will need more computation time comparing to the previous case.

5.3 Reconstruction in the presence of noise

In this part, the reconstruction of the spherical scatterer is done in the presence of random noise. Figure 8A shows the reconstruction in the noisy medium, and Figure 8B demonstrates the reconstruction in the same mesh grid without any noise. Obviously, by adding the random noise, the reconstruction process becomes more challenging, but it could return the approximate features of the scatterer. The amplitude of the imposed noise could be altered for the various tests, but it is chosen to be 50% of the actual value ($N_a = 0.5$).

6 DISCUSSION

In this section, it is attempted to validate the results and show the advantages of implementation. Therefore, the article is compared to Reference 34 in a specific condition. While comparing the numerical results with the mentioned paper, two key points are considered:
FIGURE 7  Minimum distance test (A) scatterers and (B) reconstruction

FIGURE 8  Reconstruction (A) in the presence of noise and (B) in a noiseless medium
1. Accuracy.
2. Speed.

In Reference 34, it is tried to return the 3D image of the scatterers in free space. What’s more, linear sampling method is used to solve the forward scattering problem, where the ACO algorithm is chosen to return the permittivity of the target in 25 iterations. Also, the additive Gaussian noise in this article is equal to 10% of the actual value. In reconstructing the features of the scatterers, nine antennas are used as the transmitting system, and 18 antennas are added to the problem to receive the scattered fields. Finally, it should be mentioned that the imaging medium is symmetric and homogenous. Also, the authors compared the numerical results to Reference 34 in the referred paper, which validates the work. Besides, it is tried to test the implementation for different locations and permittivity in solving the problem in the mentioned paper. However, the implementation in this article is different from Reference 34 as below.

1. The imaging is done inside a PEC cavity which makes the imaging process complicate.
2. FDTD and TFSF methods are used to directly calculate the scattered and total fields in the imaging medium without solving the scattering equation.
3. An optimized CG algorithm alongside the combined Tikhonov regularization term is implemented to solve the problem using only three iterations. Meanwhile, the implemented algorithm in Reference 34 takes 25 iterations to reconstruct the 3D image.
4. Scalar Green’s function is applied inside the cavity by considering the lossy medium in solving the problem.
5. The additive noise is about 50% of the actual value of the incident field.
6. One transmitter and one receiver antenna are used in reconstructing the 3D image of the targets in a configuration like.34
7. It takes about 10 s to reconstruct the image from the scattered fields.

As an example, Figure 9 is a comparison of a spherical target for the implementation in this article and Reference 34 where Figure 9A demonstrates the image reconstructed using the approach introduced in this article, and
TABLE 1  Simulation details and results

| Features | Main paper | Reference 34 |
|----------|------------|--------------|
| $\varepsilon_r$ | 2          |              |
| $\sigma_r$ | 0.1        |              |
| $\varepsilon_m$ | 1.2        | 1            |
| $\sigma_m$ | 0.5        | 5.5e–15      |
| $\gamma$ | 0.0162     | 0.13         |
| $\varepsilon_{\text{ref}}$ | 2          | 1.56         |
| $N_{\text{eval}}$ | 1          | 45.6         |
| $N_{\text{inv}}$ | 1          | 25           |
| Elapsed time | 21.160643 s | 25 min       |

TABLE 2  Comparison between the combined and Tikhonov regularization terms

| No. | Convergence error | Elapsed time |
|-----|-------------------|--------------|
|     | Combined | Tikhonov | Combined | Tikhonov |
| 1   | 1.01e34   | 7.10e33  | 3.03 s   | 12.54 s  |
| 2   | 2.60e19   | 7.28e31  |          |          |
| 3   | 7.30      | 3.71e29  |          |          |
| 4   | –         | 2.89e27  |          |          |
| 5   |           | 3.60e13  |          |          |
| 6   |           | 4.80e11  |          |          |
| 7   |           | 2.09e9   |          |          |
| 8   |           | 1.85e2   |          |          |

Figure 9B is the image of a same target in the reference paper. In addition, it should be mentioned that the simulated sphere is characterized by $\varepsilon_r = 2, \sigma_r = 0.1, r = 10 \text{ cm}$. Table 1 shows the configuration and results for both approaches. As it is shown in Table 1, because the size of the scatterer is big enough, the reconstruction process in this article is done using only three iterations. The elapsed time is reduced in this article because of two main reasons:

1. The low number of transmitter and receiver antennas.
2. Combined regularization term and optimized CG algorithm, which helps control the error using a low number of iterations.

Converging depends partly on the features of the medium, such as being symmetric or not, but sometimes the shape of the scatterer and the shape of the chamber could make the reconstruction process much harder. For example, the scattered waves in the presence of a cubic scatterer and chamber are not in good order. Therefore, it needs a higher iteration number in inverse scattering algorithm and many transmitter and receiver antennas to return the permittivity of the scatterer. However, it is done in this article using three iterations besides one transmitter and one receiver antenna.

Table 2 compares the convergence error and elapsed time for the inverse scattering problem derived using Tikhonov and combined regularization terms. By using the introduced approach in this article, the reconstruction is obtained in
a less iteration number. To complete the discussion section, the implementation in this article is compared to similar works\textsuperscript{35,36} in Table 3. It is attempted to compare methods and general results in this article to show the advantages of article. In determining the number of receiver and transmitter antennas, the quality of imaging is a key point. Because the obtained results are acceptable, the number of antennas was not increased.

Besides, because the imaging medium is homogenous, the location of the antennas in the scattered field region did not make a significant difference in the results. In determining the number of receiver and transmitter antennas, the quality of imaging is a crucial point. Because the obtained results are acceptable, the number of antennas was not increased. Also, changes in the location of the antennas in the scattered field region did not make a significant difference in the results.

7 CONCLUSION

3D microwave imaging was done in this article to reconstruct the features of scatterers inside a cavity. Imaging was done using the scalar Green’s function, which helps control the complexity by eliminating any need to dyadic Green’s function. Also, there is one incident plane wave and one receiver antenna, which is considerable comparing to similar works. TFSF and FDTD techniques are used to calculate the scattered fields directly without solving the scattering equation. The optimized CG method is implemented alongside the combined regularization term to reconstruct the unknown objects with the minimum number of iterations. Besides, the computation time of the 3D inverse scattering problem and capability of the algorithm in reconstructing multi scatterers in the imaging medium is noticeable.

CONFLICT OF INTEREST

I state that there is no conflict of interest. Also, I do not have any relationships or support that might constitute a conflict of interest in the future.

AUTHOR CONTRIBUTIONS

Omid Babazadeh Astmal: Conceptualization (equal), data curation (equal), formal analysis (equal), funding acquisition (equal), investigation (equal), methodology (equal), project administration (equal), resources (equal), software (equal), supervision (equal), validation (equal), visualization (equal), writing – original draft (equal), writing – review & editing (equal).

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1002/eng2.12466.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

ORCID

Omid Babazadeh Astmal https://orcid.org/0000-0003-2798-9309
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**How to cite this article:** Babazadeh O. Fast 3D microwave imaging inside cavity with minimum number of antennas and modified inverse algorithm. *Engineering Reports*. 2022;4(3):e12466. doi: 10.1002/eng2.12466