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2D Microwave Image Reconstruction of Breast Cancer Detector Using a Simplex Method and Method of Moments

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Abstract

This paper presents a tumor detection system for breast cancer that utilizes two-dimensional (2D) image reconstruction with microwave tomographic imaging. The breast cancer detection system under development consists of 16 transmit/receive antennas, and the microwave tomography system operates at 900 MHz. To solve a 2D inverse scattering problem, the method of moments (MoM) is employed for forward problem solving, and the simplex method employed as an optimization algorithm. The results of the reconstructed image show that the method accurately shows the position of a breast tumor.

Key words : Breast Cancer Detector, Microwave Tomography, Image Reconstruction.

Ⅰ. Introduction

Microwave tomography is one method that has been proposed to complement X-ray mammography. Detection of tumors at microwave frequencies via microwave imaging has been proposed on the basis of the significant contrast in dielectric properties between malignant tumors and normal fatty breast tissue [1]. Several research groups have been investigating microwave tomography for breast cancer detection [2～11]. The chirp-pulse microwave computerized tomography (CP-MCT) system has also been developed by Miyakawa *et al.* in order to perform non-invasive thermometry of the human body [12～14].

With regard to our methods, the method of moments (MoM) forward problem solver with triangle basis functions to implement the inverse scattering was described by Kim *et al.* [15]. We have studied breast cancer detection using confocal microwave imaging (CMI) in the past [16, 17]. Currently we are developing a breast cancer detection system using the microwave tomography method.

This paper presents a breast cancer detection system for electromagnetic imaging of cylindrical dielectric objects using the MoM forward problem solver and the simplex method optimization algorithm. The problem discussed here is the reconstruction of the relative permittivity and the conductivity of a dielectric cylinder embedded in a homogeneous background medium, with the knowledge of the incident electric field and the measured scattered electric field of the breast cancer detection system. The MoM with pulse-basis functions and point matching is employed to discretize the equations for the scattered electric field and the total electric field inside the object [18, 19]. The images were reconstructed using the measurement data from the prototype system, and the feasibility of the system and quality of the reconstructed image was tested.

Ⅱ. Background for Microwave Tomography System

Active microwave tomography imaging involves illuminating a breast with microwaves and then forming images from electromagnetic energy transmitted through or reflected from the breast. Fig. 1 shows the fabricated experimental system implemented for the study. The system has 16 monopole antennas and a liquid container (tank or bath). The liquid was used to have a good matching between the measuring dielectric object and the antennas. When an antenna transmits the electromagnetic field, the other 15 antennas receive the scattered electromagnetic fields. The transmitting antenna is rotated in turn along a circular path with a radius of 7.5 cm. Thus, 240 sets of measurement data are available in total for image reconstruction. The operating frequency of this system is from 500 MHz to 3 GHz, but is now measured at 900 MHz for an image reconstruction in this study.

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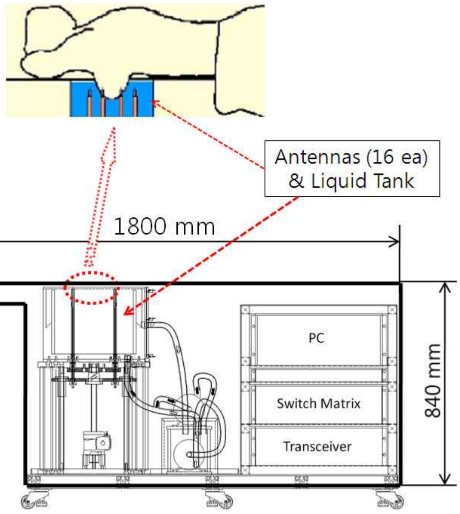


Fig. 1. Structure of hardware for microwave tomography breast cancer detection system.

Ⅲ. Forward Scattering Problem

Fig. 2 shows the procedure of the image reconstruction from the forward and inverse scattering problems. The image reconstruction problem consists of a direct (forward) scattering problem and an inverse scattering problem. In the forward algorithm, the scattered eletcromagnetic fields from the object (attributable to a transmitting antenna) are calculated at each receiving antenna position. The computed electric fields obtained from a direct scattering problem are then compared with the scattered electric field measured at the observation domain. The nonlinear reconstruction procedures using optimization algorithms are applied to obtain the electrical properties of the breast.

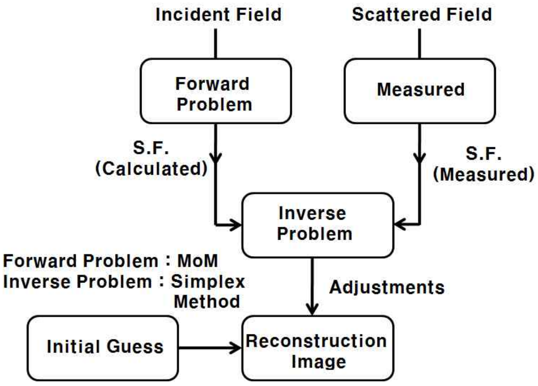


Fig. 2. Flowchart for image reconstruction.

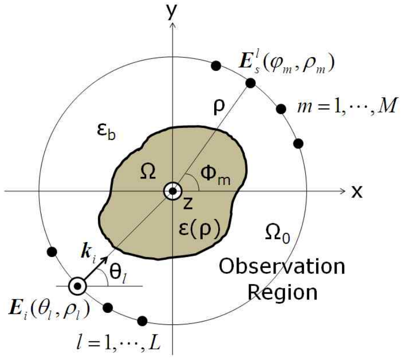


Fig. 3. Incident electric fields and scattered fields for the inverse scattering problem.

Fig. 3 shows the investigation object containing a cylindrical dielectric scatterer of arbitrary bounded cross section, incident electric fields, and scattered fields. Consider a 2D cylindrical dielectric object with relative permittivity $\epsilon(\rho)$ located in a homogeneous background medium of relative permittivity ϵ_b. The background medium is now assumed to be free space. The dielectric object with cross section Ω is assumed to be infinitely long along the z-direction. An incident electromagnetic plane wave $E_i(\theta, \rho)$ successively illuminates the object at an angle θ with the x-axis. After successive illumination of the incident plane wave by a set of L incident waves characterized by z-directed electric fields $E_i(\theta_l,\rho_l)$, $l=1$, $2,\cdots$, L, the scattered electric fields $E_s^l(\phi_m,\rho_m)$ arising from multiple scattering interactions between incident waves and the unknown object outside the dielectric object can be described in $m_{(l)}=1_{(l)}$, $2_{(l)},\cdots$, $M_{(l)}$, $l=1$, $2,\cdots$, L by the following equation:

$$E_s^l(\phi_m,\rho_m) = k_0^2\iint_{\Omega} c(\rho')E_t(\phi_m,\rho')G(\rho_m,\rho')d\rho', \quad \rho\in\Omega_0 \tag{1}$$

where Ω_0 denotes a domain outside of Ω, k_0 is a free-space wavenumber, $c(\rho)$ is a contrast function (object function) expressed as $c(\rho)=\epsilon(\rho)-\epsilon_b$, and G is the two-dimensional Green's function for the background region as expressed as

$$G(\rho,\rho') = -\frac{j}{4}H_0^{(2)}(\sqrt{\epsilon_b}k_0|\rho-\rho'|) \tag{2}$$

where $H_0^{(2)}$ is the Henkel function of zeroth order and 2nd kind, and $|\rho-\rho'| = \sqrt{(x-x')^2+(y-y')^2}$.

In equation (1), the total electric field $E_t(\phi, \rho)$ expressed as the sum of the incident and the scattered electric fields satisfies the following integral equation

$$E_t(\phi,\rho) = E_i(\theta,\rho) + k_0^2\iint_{\Omega} c(\rho')E_t(\phi,\rho')G(\rho,\rho')d\rho', \quad \rho\in\Omega \tag{3}$$

The angles of incidence field are $\theta=\theta_l$, where $l=1,2,$

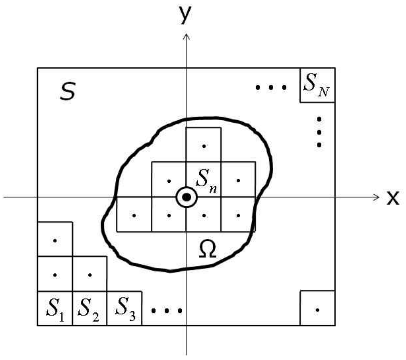


Fig. 4. Incident electric fields and scattered fields for the inverse scattering problem.

$\cdots, L$. For each angle of incidence, the scattered electric fields are measured at field points $\rho=\rho_m$ with angles $\phi=\phi_m$ along a circle of radius ρ, where $m=1, 2, \cdots, M$.

In this paper, to numerically deal with (1) and (3), the method of moments with pulse-basis functions and point matching is employed and discretized to obtain the fields. Fig. 4 shows a configuration for the MoM. The reconstruction region S containing the background medium and the dielectric object is subdivided into N square cells S_n, where $n=1, 2, \ldots, N$.

The problem unknowns, total electric field inside the dielectric object, and the contrast function are expressed as

$$E_t(\phi,\rho') = \sum_{n=1}^{N} e_n(\phi) F_n(\rho') \tag{4}$$

$$c(\rho') = \sum_{n=1}^{N} c_n F_n(\rho') \tag{5}$$

where $F_n(\rho')$ are pulse functions defined as

$$F_n(\rho') = \begin{cases} 1, & \rho' \in S_n\,, \\ 0, & \rho' \notin S_n\,. \end{cases} \tag{6}$$

e_n and c_n are the unknown coefficients to be solved for the total electric field and the dielectric constants.

By substituting (4) and (5) into (3), then the integral equation (3) is transformed to the linear equation. The scattered field is calculated as follows for a given $c(\rho')$.

$$\begin{aligned} &E_s^l(\phi_m, \rho_m) \\ &= k_0^2 \iint_{S_n} c(\rho') \sum_{n=1}^{N} e_n(\phi) F_n(\rho') G(\rho_m, \rho') d\rho' \end{aligned} \tag{7}$$

Ⅳ. Inverse Scattering Problem

We performed the microwave tomography study for breast cancer detection system using the MoM as the forward problem. For the inverse scattering problem, we used the simplex method. The measured data sets to be reconstructed were acquired by the breast cancer detection system as shown in Fig. 1.

The inverse scattering problem can be formulated as the solution to the matrix equation for the unknown expansion coefficients of a contrast function, which is expressed as a function of the relative permittivity of the dielectric object. From (4) and (7), the contrast function is expressed as follows.

$$E_s^l(\phi_m,\rho_m) = \sum_{n=1}^{N} c_n A_n^l(\phi_m,\rho_m) \tag{8}$$

where

$$\begin{aligned} A_n^l(\phi_m,\rho_m) &\equiv A_{nm}^{\ell} \\ &= k_0^2 \iint_{S_n} E_t(\theta_\ell,\rho') G(\rho_m,\rho') d\rho' \end{aligned} \tag{9}$$

In the detection system, the polar angles of incident field due to monopole antennas for transmitting are assumed to be $\theta=\theta_\ell$, $\ell=1, 2, \ldots, L$. For these angles of incident, measurements of the scattered electric field are made at observation points with $\phi=\phi_m$ along a transmitting and receiving antennas circle of radius ρ_m, where $m=1, 2, \ldots, M$. From the Equation (8), using the measured electric fields $\widetilde{E_{sm}^l}$ instead of $E_s^l(\phi_m, \rho_m)$, the unknown expansion coefficients of the contrast function may be determined by the least-squares sense

$$\sum_{l=1}^{L} \sum_{m=1}^{M} \| \sum_{n=1}^{N} c_n A_{nm}^l - \widetilde{E_{sm}^l} \|^2 = \min \tag{10}$$

where $\widetilde{E_{sm}^l}$ refers to the scattered electric field measured at $\theta=\theta_l$ and $\phi=\phi_m$, and $\| \bullet \|$ denotes a Euclidean norm. A_{nm}^{ℓ} is the element of a $N \times M$ matrix as shown in (9).

Equation (10) may be solved in the simplex method. The simplex method now takes a series of steps, most steps just moving the point of the simplex where the function is largest through the opposite face of the simplex to a lower point. These steps used in this paper are called reflections, expansions, contractions, and reductions [20, 21]. The contrast function can be reconstructed by the minimization of a cost function, which is written as the sum of direct scattered field and the measured scattered electric fields of the breast cancer detection system.

Ⅴ. Reconstruction Results

The 12×12 cm square region containing the object and the background medium is uniformly subdivided into 12 ×12 elementary square cells. The transmitting antenna is rotated in turn along a circular path with radius of 7.5

cm. The fat has a diameter of 10 cm, and the tumor is the small circle with the relative permittivity of 61.9. The radius of 10 mm is used for reconstruction study.

Fig. 5 shows how the constructed image is defined for the sectional view of the real breast and how 16 antennas and tissues for image reconstruction are arranged in this study.

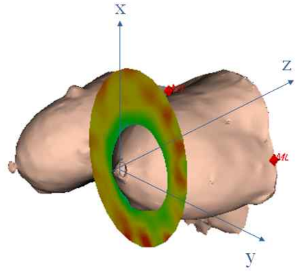
Table 1 represents the electrical properties of tissues used in the study. The images consist of the permittivity image and the conductivity image.

Fig. 6 shows the original and reconstructed permittivity distribution obtained from the simplex algorithm. As shown in Fig. 6, we can see that the position of the reconstructed tumor image is almost same as the real position of the tumor.

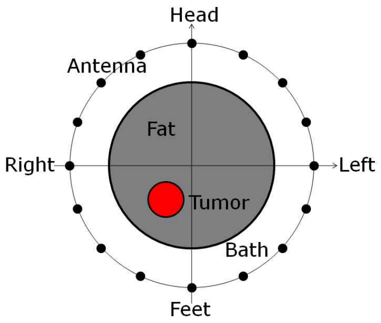
Fig. 7 shows the original and reconstructed conductivity distribution obtained from the simplex algorithm. We can also see that the position of the reconstructed tumor image correlates closely with the real position of the

Table 1. Electrical properties of tissues used for image reconstruction.

	Relative permittivity	Conductivity(S/m)
Bath	31.7	1.07
Fat	21.3	0.87
Tumor	61.9	0.79

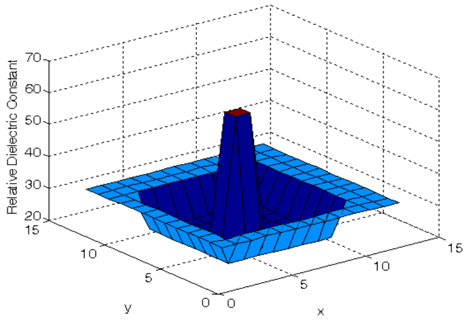


(a) Sectional view of a breast and its simplified layout for imaging

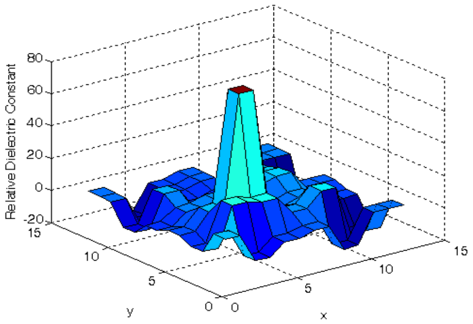


(b) Layout of 16 antennas and tissues

Fig. 5. Structure of 16 antennas and tissues for image reconstruction.

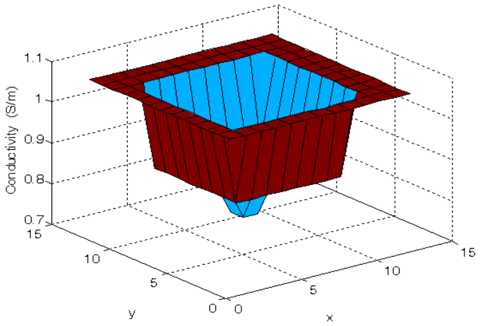


(a) Original profile

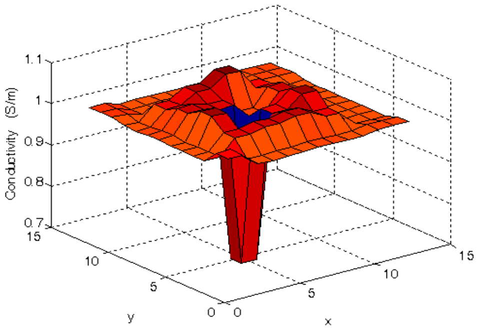


(b) Reconstructed result

Fig. 6. Reconstructed permittivity based on the simplex algorithm at 900 MHz.



(a) Original profile



(b) Reconstructed result

Fig. 7. Reconstructed conductivity based on the simplex algorithm at 900 MHz.

tumor. Some mismatches in the values of permittivity and conductivity are also found in this case. The permittivity and conductivity values are not matched exactly in these distributions but the positions of tumor are well matched. We suspect this inexact matching comes from the smoothing phenomenon for a high-contrast and relatively small object during reconstruction, and the difference between the real situation and 2D approximation.

During this study, we found the quality of the real measurement data is very important. Most studies are conducted using computer simulations. However, the real situation is very different from the ideal situation. How we can obtain a high-quality measurement data without the test being made equivocal by environmental noise is the most crucial requirement for microwave image-reconstruction study. Fortunately, it was possible to perform this study with a good hardware system.

Ⅵ. Conclusion

This paper presents an evaluation of the technical specifications and effectiveness of a tumor detector for breast cancer that reconstructs images using 2D microwave tomography. We used the MoM for forward calculation, and the simplex method as an optimization algorithm. The results show that the permittivity and the conductivity values are not matched exactly, but the positions of tumor are well matched. Further improvements on image reconstruction and three-dimensional analysis remain a problem to be pursued in future work.

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