A Novel Data-Dependent Microwave Imaging Technique to Detect Malignant Breast Tissues

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1. Introduction

Microwave imaging approaches including both microwave tomography and radar-based imaging have shown potential for detecting and monitoring the malignancies of breast cancer. In radar imaging, the breast is illuminated by a microwave pulse and the malignant tissue is identified based on the backscattered signal collected at the receiver antenna array. The physical basis for microwave breast tumor detection is the presence of dielectric contrast between malignant and healthy tissue that exists at microwave frequencies. Confocal microwave imaging (CMI) method [1], [2], which focuses only on significant scatterers instead of quantitatively computing of the dielectric properties of the whole breast, provides a simple but effective way for image reconstruction. Another approach [3] is to combine the time of arrival (TOA) technique to localize the tumor’s position. This paper presents an alternative way of combining TOA and data dependent beamforming methods to localize the malignant breast tissue. In this method, we first estimate the scattered energy using the beamformer and then employ the TOA method to localize the target tissue. However, the scattered energy from the surrounding clutter can be a source of interference that can hinder the detection of the true target response thus leading to localization problems. Particularly, in low SNR scenarios, the interference from clutter can be severe. Use of conventional beamforming techniques such as MVDR beamforming in such scenarios can lead to higher estimation errors. To alleviate such problems, in this paper we investigate the use of an efficient data dependent beamforming technique.

2. Electromagnetic Breast Model

The breast is modeled as a 2-D lossy dielectric numerical phantom [3] with a uniform linear antenna array located on the surface of the breast as shown in Fig 1. The UWB probing signal has the range from 1GHz to 11 GHz. Tumor in the early stage normally has a small size and is surrounded by normal tissues. Both the target tumor tissue and other surrounding tissues are assumed to be lossy elliptical dielectric cylinders immersed in a lossy homogeneous dielectric background. Each antenna element of the ULA transmits the probing UWB pulse in turns and all the other antennas receive the backscattered signals. We employ modulated Gaussian pulse excitation. The incident UWB pulse is generated by:

$$E(t) = E_0 \sin(\omega_0 (t - 8T)) \left(1 - \frac{t - 8T}{T}\right) \exp\left(-\frac{(t - 8T)^2}{4T^2}\right)$$

where $\omega_0$ is the carrier frequency that equals to $12\pi \times 10^9$ rad/s and $T$ is the duration of pulse that equals to 50 ps. It is well established that at UWB microwave frequencies, there is a dielectric contrast between malignant and normal breast tissues and this contrast can vary [5]. This variation can be represented by the ratio of the absolute dielectric variation to the median value dielectric contrast ($\gamma$) between malignant and normal tissues [3]. The dielectric properties with different $\gamma$ could represent inhomogeneous breast tissues at different regions in the breast model that is derived from the MRI images. Normally, the normal fatty tissues have $\gamma \leq 0.1$ [5] and for diseased tissues $2 \leq \gamma \leq 7$ [5]. The reflection by the skin layer can be significant and here we
assume that the skin reflection is perfectly removed. It is further assumed that the antennas are immersed in a coupling medium whose dielectric properties match the permittivity of the breast tissue. The varying dielectric properties of the breast are described by the first-order Debye dispersion equation. The backscattered response from breast tissues is calculated using the method of moments (MOM) [3].

3. Beamforming and Localization

A spatial filter can be designed by using the standard MVDR method to allow the backscattered signals from the target tissue to pass through while attenuating signals from surrounding clutter sources. In this paper, we employ the minimax regret beamformer (MXR) [7] that can be regarded as a weighted MVDR. The minimax regret beamformer maximizes the signal-to-interference-plus-noise ratio (SINR) and at the same time minimizes the mean squared error (MSE). Thus it improves the MVDR estimates. Assuming that the steering vector has no bias, the MVDR beamformer is given by:

$$\hat{w}_{MVDR} = \frac{\hat{R}^{-1}_{xx}a(\theta)}{a^H(\theta)R^{-1}_{xx}a(\theta)}$$

The array time-average correlation is $$R_{xx} = \frac{1}{N} \sum_{n=1}^{N} x(n)x^H(n)$$. The minimax beamformer is given by [7]:

$$w_{\text{minimax}} = \beta \hat{w}_{MVDR}$$

where the constant $$\beta$$ is given by:

$$\beta = \frac{\sqrt{1 + R^{-1}_{xx}a^H a}}{1 + \sqrt{1 + R^{-1}_{xx}a^H a}}$$

$$|\psi(t)|^2$$ is defined by: $$\frac{1}{\gamma} \left( \sqrt{1 + \gamma^2} - 1 \right)$$, where $$\gamma = a^H R^{-1}a$$. The output of the minimax beamformer is $$\hat{s} = w_{\text{minimax}}^T y(t)$$, where $$y(t)$$ is the received signal. Using this, the backscattered energy can be calculated as $$p = \sum_{t=1}^{N} |\hat{s}(t)|^2$$, where $$N$$ is the number of snapshots.

It is noted that the error of localization can vary depending on the position of target tissue within the breast. In our simulation, we first set that the true positions of two tumors to be at (2, 3) cm and (0, 1.5) cm within the breast phantom. In addition to the target tissue, 35 breast tissues with different elliptic cross-sectional area are also considered in the close proximity. Next, the MXR beamformer is steered to various positions to accurately differentiate the backscatter energy due to the tumor from other surrounding tissues. The output of the beamformer provides more accurate amplitude estimation than MVDR beamformer and produces an image based on the intensity of backscattered energy. The image produced by the MXR beamforming is shown in the Figure 2(a), where the SNR at the receiver is chosen to be -21dB. The two highest peaks represent energy due to the tumor and other lower peaks due to the scattering from surrounding normal tissues. Once the beamformer accurately estimates the backscattered energy from the tumor as described above, the time of arrival (TOA) can be used to estimate the tumor’s location. The tumor locations estimated by TOA are shown in Figure 2(b). For the sake of comparison, the results by using MVDR at the same SNR level are also given in Figure 3(a), where the tumor responses are overwhelmed by the interference from clutters. The strong interference will lead to the big error of tumor localization shown in Figure 3(b). The estimation of tumor located at (2, 3) cm has larger bias than the tumor at (0, 1.5) cm due to the geometry of uniform linear array (ULA). The bias is measured by root-mean-square-error (RMSE). The RMSE of tumor located at (2, 3) cm and (0, 1.5) cm are 0.365 cm and 0.0076 cm, respectively. Our simulations demonstrate that, when ULA is employed the TOA method will result in some inherent localization bias in certain regions within the breast as shown in
Figure 4 (a). This bias can be minimized by using other antenna array geometries such as circular array as shown in Figure 4 (b).

4. Conclusions

We present the application of minimax beamforming to differentiate the target tissue scattering response from clutter even at low SNR levels, so that accurate and robust localization of the tumor’s position can be made. We demonstrate the performance of the proposed method using the simulations performed on a 2-Dimensional computational electromagnetic breast model.

5. Figures and Tables

Figure 1: The two-dimensional numerical breast phantoms with elliptic cross-sections in different structural clusters. Two tumors with $\gamma = 4, 5$ and cross-sectional area $= 9\pi (\text{mm}^2)$ are located in (0, 1.5) cm and (2, 3) cm, respectively. Clutters are uniformly distributed in each cluster.

Figure 2: The reconstructed image of breast tissues using MXR beamforming and tumor locations using TOA technique. (a) The different backscattered energy intensities due to both tumors and fatty tissues at SNR= -21dB. (b) The estimated tumor locations. Two cross symbols represent the true positions of tumors and the circular symbols represent the estimated tumor locations.
Figure 3: The localization of breast tumor using standard MVDR beamforming and TOA technique. (a) The different backscattered energy intensities due to both tumors and fatty tissues at SNR= -21dB. (b) The estimated tumor locations. Two cross symbols represent the true positions of tumors and the circular symbols represent the estimated tumor locations.

Figure 4: The RMSE with different antenna array geometry. (a) Uniform Linear Array (ULA) with 7 antenna elements. (b) Circular Array with 7 antenna elements.

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References