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Permittivity Estimation for Breast Cancer Detection Using Particle Swarm Optimization Algorithm

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***Abstract*—In this paper, particle swarm optimization (PSO) algorithm is used to estimate the permittivities of the tissue layers at microwave frequency band. According to the literature, microwave radiometry (MWR) is potentially a promising cancer detection technique. In addition, breast cancer is an appropriate candidate of MWR due to the breast's exclusive physiology. Several algorithms have been evaluated for analyzing the measurement data and solving the inverse scattering problem in MWR, and different levels of accuracy have been reported. In this paper, the potential of PSO in solving this problem is demonstrated at 1-2.25 GHz. Two distinct algorithms are developed for the two considered scenarios. In the first scenario, we assume no a priori knowledge of the tissue under the test, whereas, in the second scenario, a priori knowledge is assumed. It is noteworthy that, there are only a few research articles studying PSO for permittivity estimation. However, since these studies underestimate the loss encountered by the test samples, the methods are not valid for body tissue case. Here, measurement-based loss coefficients, reported in the existing literature, are included in the calculations. It is shown that the algorithm converges relatively fast, and, distinguishes between different tissues with an acceptable accuracy.**

***Index Terms*—Breast Cancer, Microwave Tomography, Antenna.**

I. Introduction

It is well known that the early detection of the breast cancer significantly increases the survival rate of the patient. In addition, it makes the treatment and recovery procedure more tolerable. Although X-ray mammography has been recognized as the most recommended breast cancer tomography method, it's 20% detection failure and ionizing feature are serious drawbacks to this procedure. Some other techniques, such as ultrasound, and MRI, with promising results are available as well. Nonetheless, these methods are either less accurate or more expensive when compared to X-ray mammography method. Consequently, they have not been used widely, particularly for the routine yearly checkups. Moreover, interesting initial results have been published on a number of more recent techniques at microwave, near-infra-red, and terahertz frequencies. Ongoing studies at different educational and medical centers are focused on validating the theoretical and experimental results of these methods. In this paper, we concentrate on microwave (MW) frequency techniques due to their ease of implementation and their promising potential as inexpensive and reliable diagnostic tools. The reason for choosing MW over higher frequencies is the poor penetration of high frequency RF in human tissue. In addition, the standard size of the MW components allows one to realize a non-invasive, portable detector. It is important to note that utilizing non-ionizing MW radiation has gained a great deal of interest in cancer detection and monitoring. A good list of research studies in this area can be found in [1].

Two main issues are observed in the reported MWR studies. First, there was lack of comprehensive studies involving a large number of in-vivo measurements for validating and modifying the theoretical methods. Second, the average success rates of detecting malignant tissues in non-superficial areas of the breast were generally low in these studies. The second problem is partly created by the fact that the previous studies underestimate the non-negligible variations in the tissue characteristics from person to person and even in a single person at different times or under different experimental circumstances. In one of the best studies, reported in [1], 488 samples from breast reduction surgeries and 319 samples from cancer surgeries were analyzed in 0.5-20 GHz frequency range; it was shown that the electrical properties of the tissue span over a wide range. In another study [2], it was shown that these properties were highly affected by the measurement setup. Hence, here, we propose using random variables for tissue characteristics instead of assuming deterministic variables. In addition, PSO, as a random-based evolutionary algorithm, is proposed as an efficient search algorithm to determine the permittivity of the breast tissue layers using an inverse scattering method. Since array radiators are generally used for cancer radiometry, the interaction of a narrow beam with a multi-layer structure can be modeled as planar wave scattering problem. Furthermore, the array allows for the localization of the malignant tissue. This problem has been studied in the literature for lossy multi-layer structures; for example see [3] and [4]. In this study, the accumulated error for both amplitudes and phases of the reflection and transmittance coefficients are utilized as the objective function of the search algorithm.

In [5] and [6], PSO was used to estimate the permittivity of the layers in a multi-layer structure. However, the medium under the test was assumed to be lossless or low-loss. Although this assumption significantly decreases the calculation complexity, it is not a valid assumption for tissue. Body tissues are absorbing media. Adding this level of loss to the calculations increases the optimization cost, and also makes it necessary to feed the calculation process with more known data obtained from additional measurements.

The goal of this study is to demonstrate that PSO successfully identifies the contrast between the permittivities of the breast tissue layers, and therefore, can detect the signatures of malignant tissues. Section II briefly reviews the distinctions

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between normal and malignant tissues inside the breast. The breast structure is modeled as a multi-layer mass with respect to its physiological composition in section II. Then, the estimation approach and its results are demonstrated in sections III and IV, respectively.

II. Two-Dimensional Breast Model

In order to correctly model the breast tissue, a study of the breast composition is required. The breast is a heterogeneous mass of glandular, fatty, and fibrous tissues positioned over the muscles of the chest wall and is attached to the chest wall by fibrous strands. It is interesting to know that, there is wide variation in the proportion of blood supplied by arteries in the breast; symmetry of the superficial venous plexus is not apparent either [7]. Thus, a deterministic model can never represent the breast tissue accurately.

The dielectric properties of normal breast tissue are primarily determined by its adipose content. In [1], it is shown that the contrast of dielectric properties between malignant tissue and normal adipose-dominated tissue (85-100% adipose) is considerably high. However, the contrast of dielectric properties between malignant tissue and normal glandular/fibroconnective tissue (0-30% adipose) is low. According to [1], the vast majority of breast cancers arise in the glandular region of the breast. Therefore, a breast cancer tissue is mostly malignant glandular tissue. As it is shown in Figs 10-12 of reference [1], the dielectric properties of normal (adipose, glandular and fibroconnective), malignant (invasive and non-invasive ductal and lobular carcinomas) and benign (fibroadenomas and cysts) breast tissue samples span over a wide range. Therefore, random variables are introduced for modeling the permittivities in the next section.

In the case of narrow beam radiator, which is considered in this paper, two dimensional models are adequate for analysis. As it is shown in Fig. 1, considering the breast physiology, different models of breast, e.g. 5-layer and 7-layer models, can be suggested with different levels of accuracy and simplicity. The total thickness of the tissue is not a fixed value for all women, however, in this paper, it is assumed to be 4.4 cm. Considering that the breast should be placed between a transmitter and a receiver which slightly squeeze the tissue, this thickness is reasonable. The total thicknesses of the glandular and adipose layers are 10 mm and 20 mm, respectively. A 5 mm layer of tissue with 31-84% content of adipose is also considered between adipose and glandular tissues. This layer is combined with the adipose-dominated layer in the 5-layer model.

Breast cancer detection at MW band is highly sensitive to the liquid content of the tissue. It has been shown that, the overall ratio of the blood flow in the breast tumor is 4.7 to 5.5 times larger than that of the normal tissue (this value is usually approximated by 5.1 [2]). Therefore, tumors can be detected using MW radiation. It is also a critical part of the technique to define the radiation frequency/ies. Although the detection resolution improves at higher frequencies, the absorption rate increases as well. Thus, it is difficult, if not impossible, to detect deep tumors using high frequency radiometry. MW band has an exceptional position in the spectrum that can offer both acceptable resolution and sufficient penetration depth required for breast cancer detection. We demonstrate the simulation results for 1-2.25 GHz frequency range in this paper. However, the introduced technique can be used for any other frequency range as well.

III. Estimation Approach

To represent the dielectric constant of each tissue, a random variable with uniform distribution is defined. The variation spans of the random variables are chosen according to the following two scenarios.

- Scenario 1: assuming no a priori knowledge.
- Scenario 2: assuming a reasonable a priori knowledge.

In scenario 1, the random variables can possess any value between the lowest possible and largest possible dielectric constants of the tissues under study. This implies that we do not assume a knowledge of the tissue samples observed by a penetrating MW radiation. It has been shown that the largest value corresponds to muscle and blood, and the lowest value corresponds to fat. Complex number PSO (CPSO) with wide search area is used for this scenario. In principle, CPSO is similar to real number PSO, except for its wider search area due to the complex number nature of the search [9]. In fact, this scenario proves that PSO has the potential of being used for any tissue other than breast, as well. This is valid as long as the penetration depth and receiver sensitivity satisfy the required thresholds of detecting scattered fields.

In scenario 2, it is first assumed that the tissue under investigation consists of a fixed number of layers. Second, the make up of each layer is initially selected randomly from a set of six tissue types that includes skin, adipose-dominated tissue, glandular tissue, 31-84% fat tissue, blood, and malignant tissue [10]. For each possible layer, a random variable, defined over a range of permittivity observed in the literature, is used to model the layer. To better organize the algorithm, discredited PSO (DPSO) is proposed in this paper. The algorithm, after a sufficient number of iterations, finds the tissue type and its corresponding best possible dielectric constant for each layer of the tissue under study. The top and bottom boundaries of the variation span related to each tissue-type are defined to be 10% higher and 10% lower, respectively, than the typical value reported in the literature [1] for that tissue. In principle, DPSO is close to the binary PSO (BPSO) technique [9]. The distinctions are: (1) In BPSO there are only two levels; whereas here, the number of levels is equal to the number of tissue-types, which is six for our breast model. (2) In BPSO, each level corresponds to a single deterministic value (either 0 or 1); whereas here, each level represents a variation span. It is shown in the next section that much faster convergence is achieved for DPSO as compared to CPSO, as one would expect.

In order to provide sufficient known parameters for PSO, bi-directional radiation at discrete frequencies and discrete incident angles are considered. Bi-directional radiation is a set of two measurements in which the transmitter and receiver roles are swapped. The two algorithms are implemented in Matlab and executed on a standard 2.83 GHz computer.

IV. Simulation Results

In this section, some of the estimation results for the two PSO algorithms for the breast model introduced in Fig. 1 are summarized for the two aforementioned scenarios.

A. Scenario 1

Figs 2-3 show the actual and estimated dielectric constants of the 5 and 7-layer structures. Both real parts and imaginary parts are estimated by CPSO. Table I shows the optimization costs in terms of the number of agents, frequencies, and incident angles, as well as convergence time in a standard computer.

Fig. 4 shows the convergence trend averaged over the agents. Eq. 1 is the fitness function used as the search criterion of both PSO algorithms.

$$f = \sum\{||R_{actual}| - |R_{estimated}|| + |phase(R_{actual}) - phase(R_{estimated})| + ||T_{actual}| - |T_{estimated}|| + |phase(T_{actual}) - phase(T_{estimated})|\}; \quad (1)$$

In (1), R and T are the reflection and transmittance coefficients. The summation in over the discrete frequencies and incident angles considered for the analysis. It is evident that by increasing the number of frequencies and incident angles, the number of the added terms in the fitness function increases, as well. Therefore, it is expected to converge to higher fitness values, although the error of the estimated dielectric constants doesn't increase. Fig. 5 shows the estimated permittivities as compared to actual ones at the studied frequencies. The variation of the permittivity as a function of frequency is clearly illustrated in this figure.

B. Scenario 2

The estimated dielectric constants and convergence trends for the second scenario are also shown on Figs 2-4. As it is expected, DPSO algorithm converges much faster and ends up with the more accurate estimates as compared with CPSO. This is also illustrated in Table I. It is observed that even single-frequency analysis can solve the problem by adding the a priori information. It should be mentioned that a lower number of agents could be considered for DPSO as compared with CPSO. However, for the sake of comparison, the same numbers are used in Table I. Fig. 6 shows the estimation results when a tumor with a thickness of 3 mm is added to the model in two different locations; namely, in one case a tumor is present inside the adipose tissue and in another scenario one tumor is present inside the glandular tissue. It is noteworthy that due to a lower contrast between the glandular tissue and tumor, it is much more difficult for the swarm to make an estimation with an acceptable accuracy when the tumor is present in the glandular tissue. However, DPSO has successfully highlighted the heterogeneity created by the tumor in both areas. It should be noted that the real part of the dielectric constant (permittivity) is a more precise indicator of tissue-type. Therefore, the imaginary parts are not shown in the figures for the sake of conciseness.

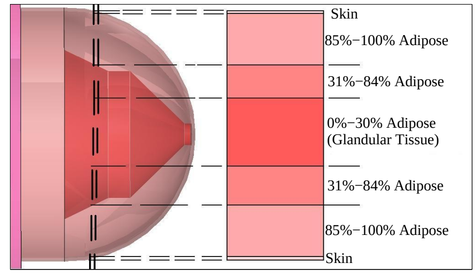

Fig. 1. Simplified two dimensional model of breast tissue.

TABLE I
OPTIMIZATION COST

Layers (Scenario)	Number of agents/frequencies/angles	Convergence time (min)
Scenario 1 5-layers	40/2/2	7.81
Scenario 1 7-layers	280/6/3	185.3
Scenario 2 5-layers	40/1/2	0.7
Scenario 2 7-layers	280/1/3	9.2

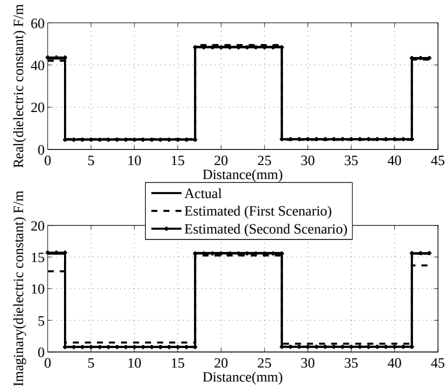

Fig. 2. Actual and estimated dielectric constants for the five-layer structure. Two frequencies (1 GHz and 1.25 GHz), and two incident angles (0 and 30 *deg*)are considered in the 1^{st} scenario. One frequency (1 GHz), and two incident angles (0 and 30 *deg*) are considered in the 2^{nd}.

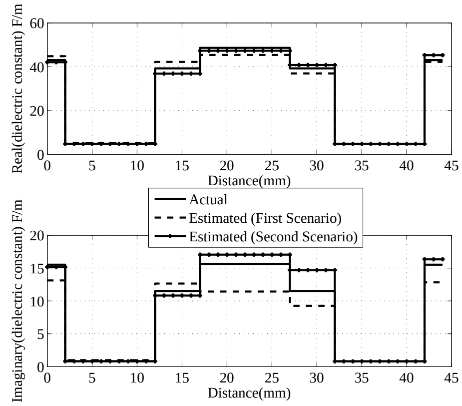

Fig. 3. Actual and estimated dielectric constants for the five-layer structure. Six frequencies (1 GHz:0.25 GHz:2.25 GHz), and three incident angles (0,30,70 *deg*) are considered in the 1^{st} scenario. One frequency (1 GHz), and three incident angles (0,30,70 *deg*) are considered in the 2^{nd}.

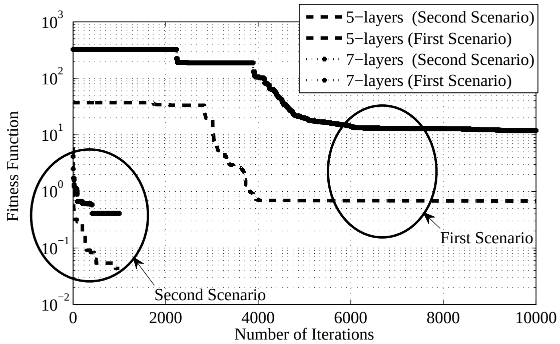

Fig. 4. Fitness function trend averaged over the agents for the two scenario.

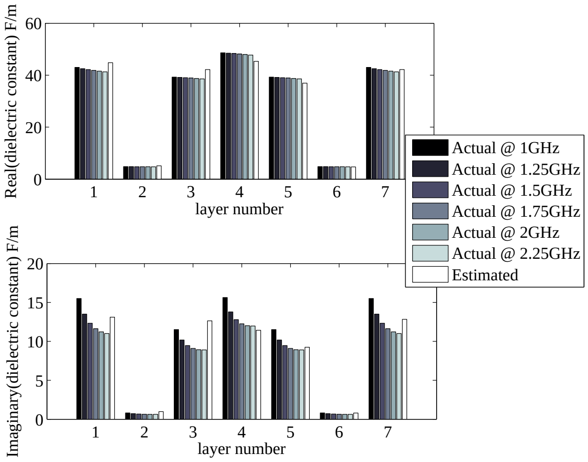

Fig. 5. Comparison of the actual values at different frequencies with the estimated values in the first scenario for the 7-layer model.

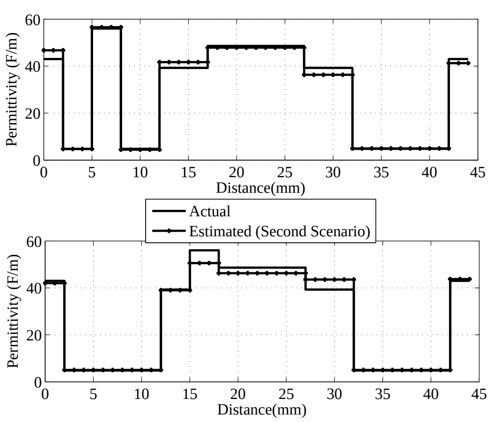

Fig. 6. Actual permittivity values and the estimated ones in the second scenario, assuming a 3 mm thick tumor in the fatty area (top) and in the glandular area (bottom).

V. CONCLUSION

The accuracy and speed of radiometry and spectroscopy techniques are directly dependent on the algorithm and mathematical approach used in processing the data collected from measurements. Due to the evident semi-random electric properties of breast tissue, in this paper, we first proposed to define random variables to model the permittivity of tissue layers, and then used PSO algorithm as a random-based search method to estimate the make up of the tissue layers. The algorithm was redesigned in two distinct formats to fit the two demanding scenarios of (1) when no a priori knowledge of the tissue is available, and (2) when the tissue layers were considered to be selected from a set of known tissue types for human breast. It was depicted in the paper that PSO successfully identifies the contrast between the permittivities of the tissue layers with an average estimation error below 10%. This accuracy is increased to an average error rate smaller than 5% in the second scenario. Obviously, by increasing the optimization cost (for instance, increasing the number of agents), the accuracy of the final responses can be improved significantly.

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