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Spatial Prior for Quantitative Breast Cancer Microwave Imaging: a Comparison Between Non-Iterative Eigenfunction-Based Inversion and Sampling Methods

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Abstract

Breast cancer imaging represents a relevant and promising application area of microwave imaging technology. As breast tissues exhibit different electromagnetic properties at microwave frequencies depending on their typology and physio-pathological status, retrieving the complex-valued permittivity allows differentiating normal and diseased tissues. Recently, efforts have been made to obtain high-quality prior information in order to improve both the accuracy and resolution of microwave imaging reconstructions. In this work, the use of prior information based on a combination of linear/orthogonal sampling method results is proposed in order to generate spatial priors to be used within the Contrast Source Inversion scheme. Results are compared to contrast source inversion images generated using prior information obtain from a non-iterative eigenfunction-based inversion method.

1 Introduction

One of the most significant biomedical applications of microwave imaging is breast cancer detection and monitoring [1]. Indeed, the specificity of microwave parameters with respect to different breast tissues allows one to differentiate healthy and tumoral tissues. However, quantitative microwave imaging exhibits a lower spatial resolution with respect to the golden standard imaging techniques, namely magnetic resonance imaging and x-ray computed tomography. Moreover, microwave imaging involves the solution of an inverse scattering problem, that is both non-linear and ill-posed [2],[3].

Researchers continue to make efforts in order to introduce new effective and reliable inversion techniques, thus improving accuracy and resolution of the resulting reconstructions. In particular, different spatial priors, that are morphological information, have been proposed and incorporate into microwave algorithms [4]-[10]. One possibility is to derive spatial priors from higher resolution modalities such as magnetic resonance imaging, computed tomography or ultrasound imaging. However, this requires a combination of microwave and other imaging modalities, which implies a more complex and expensive data acquisition and processing procedure. Another possibility is using microwave interrogation to both create the morphological prior information and to reconstruct the complex-valued permittivity, thus avoiding a multimodal imaging system or processing technique.

Recently, spatial prior has been derived from the use of a non-iterative quantitative microwave technique, based on the use of eigenfunction basis [11], and incorporated as a numerical inhomogeneous background medium into the Contrast Source Inversion (CSI) scheme [10].

An alternative way to derived spatial priors to be incorporated in the CSI scheme is proposed here, based on the use of two qualitative sampling methods [12]-[14]. Interestingly, such methods have the advantage of allowing the extraction of morphological information in almost real-time.

2 The Contrast Source Inversion Method

Microwave imaging involves the solution of an inverse scattering problem, which aims at retrieving the electromagnetic and geometrical properties of unknown targets starting from knowledge of the incident field, illuminating the region of interest, and the measurements of the corresponding scattered field. In breast cancer imaging applications, the aim is the reconstruction of the complex permittivity of tissues within the breast in order to discriminate between healthy tissues (mainly skin, fat and fibroglandular tissue) and tumoral cells.

The solution of an inverse scattering problem represents a non-trivial task, due to both non-linearity and ill-posedness [2],[3]. In the literature, different inversion methods have been proposed. The Contrast Source Inversion (CSI) method belongs to the class of non-linear quantitative methods and aims to retrieve both electrical and morphological properties of the unknown targets and tackle the problem in its full non-linear form. As such, CSI does not involve any kind of approximations and simply attempts to minimize an appropriate cost functional.

From a mathematical point of view, and by assuming 2D geometry and a TM polarized field, the problem is tackled as follows [15]:

$$\min_{\chi,W}\left[\sum_{t}\frac{\|\chi E_i+\chi A_i[W]-W\|_{l_2}^2}{\|E_i\|_{l_2}^2}+\sum_{t}\frac{\|E_s-A_e[W]\|_{l_2}^2}{\|E_s\|_{l_2}^2}\right] \quad (1)$$

wherein:

- $\chi(\boldsymbol{r})=\frac{\varepsilon(r)-\varepsilon_b(r)}{\varepsilon_b(r)}$ encodes the electromagnetic properties of the breast tissues $\varepsilon(\boldsymbol{r})$, supposed to be embedded in the imaging region D filled with a potentially inhomogeneous background medium with the complex permittivity $\varepsilon_b(\boldsymbol{r})$;
- $\|\cdot\|_{l_2}$ is the l_2-norm;
- $\boldsymbol{r}=(x,y)\in$ D;
- $W=W(\boldsymbol{r},\boldsymbol{r}_t)$ and $E_i=E_i(\boldsymbol{r},\boldsymbol{r}_t)$ are, respectively, induced contrast currents and incident electric fields in D;
- $E_s=E_s(\boldsymbol{r}_m,\boldsymbol{r}_t)$ is the measured scattered field;
- $\boldsymbol{r}_t$ and $\boldsymbol{r}_m$ are the positions of transmitting and receiving antennas which are used to probe D and measure E_s, respectively;
- A_e and A_i are short notations of the involved radiation operators.

For more details about CSI method, the interested readers are referred to [15].

3 Incorporation of Spatial Priors within CSI as a Numerical Background Medium

Unfortunately, the functional (1) is non-quadratic with respect to the unknowns χ and W. As such, any adopted local minimization procedure could be trapped in local minima and arrives at false solutions of the problem [16].

In order to avoid the occurrence of false solutions, a priori information of the unknown targets is usually exploited. For instance, in [17] a CSI scheme has been equipped with support information in order to improve the reliability of the minimization process and reduce the time to convergence. In particular, the unknown quantities W and χ are constrained to assume non-zero values only inside the target support, estimated via qualitative methods.

On the other hand, in this paper, a priori information is used not to simply constrain the unknowns, but rather to build spatial prior information to be incorporated in CSI as a numerical inhomogeneous background medium [6],[7]. More in detail, the homogeneous background is replaced with a numerical inhomogeneous background $\varepsilon_N(\boldsymbol{r})$ obtained from the available prior information. It is important to note that the use of the numerical background $\varepsilon_N(\boldsymbol{r})$ involves the redefinition of the contrast function as well as the evaluation of the Green's function and, hence, of the corresponding radiation operator.

4 Spatial priors from Non-Iterative Eigenfunction-based Inversion

The Non-Iterative Eigenfunction-based Inversion (NIEI) algorithm presented in [10],[11] is a quantitative imaging technique that first solves a set of constrained inverse source problems equivalent to the second summation in (1). The solution to these ill-posed problems is regularized by expanding the contrast sources in the eigenfunction basis of the assumed metallic imaging enclosure. Outside of the imaging domain D, constraints on the global basis coefficients ensure nullity of the contrast sources. By nature of the selected basis, the measurement data is related directly to the global contrast source coefficients and, combined with the constraints, yields a well-posed system of equations when the basis expansion is truncated appropriately and can be solved directly; details can be found in [11]. Once the contrast source coefficients are known, recovery of the contrast is straightforward yielding spatially meaningful approximations to high-contrast dielectric targets [11].

Adopting the NIEI reconstructed contrast as prior information for CSI has been shown to provide a path to improved single-modality reconstructions of the breast [10].

5 Spatial priors from Sampling Methods

In order to gain a priori information on the breast tissues, qualitative methods can be exploited. Such methods aim at acquiring only morphological characteristics of the unknown targets, giving up the reconstruction of their electromagnetic properties.

Among qualitative methods, sampling methods are probably most popular. They are based on sampling the investigation domain D over a grid of points where an indicator function is evaluated. Then, they discriminate between points inside and outside the target by plotting the relevant indicator function. Indeed, it will assume different values depending on the position of the sampling points within the target. The indicator function is bounded when the sampling point belongs to the unknown object and keeps unbounded elsewhere.

The Linear Sampling Method (LSM) [12] and Orthogonality Sampling Method (OSM) [13],[14] are two significant examples. In the LSM the indicator function is computed by solving an auxiliary linear, but ill-posed, problem and the adoption of a regularization technique is required [12]. On the other hand, in OSM the indicator function is evaluated as the scalar product between the scattered data and the pertaining Green's function [13]. Interestingly, these two sampling methods differ also in their reconstruction capability. While LSM is able to retrieve only the target support, OSM is also able to retrieve the presence of internal discontinuities in the electrical properties [14].

In this paper a new method to build spatial priors is proposed that combines both the LSM and OSM indicator maps. In particular, the information about the breast extent is extracted from the LSM indicator map, while information about fibroglandular and tumoral regions are derived by analyzing the OSM indicator map. Then, such morphological maps are modulated in amplitude according to the expected values of permittivity and conductivity of the breast tissues [18].

Details about the procedure to build spatial priors from LSM and OSM will be given at the conference. The performance of the proposed LSM/OSM combined prior will be compared to that of the quantitative NIEI eigenfunction prior in terms of both imaging accuracy and computational performance.

6 References

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