MICROWAVE IMAGING FOR EARLY STAGE BREAST TUMOR DETECTION AND DISCRIMINATION VIA COMPLEX NATURAL RESONANCES

By

Fan Yang

A Thesis Submitted for the Degree of
Doctor of Philosophy

Faculty of Engineering & Information Technology, University of Technology, Sydney
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CERTIFICATION

I certify that this thesis has not already been submitted for any degree and is not being submitted as part of candidature for any other degree.

I also certify that this thesis has been written by me and that any help that I have received in my research work, preparing this thesis, and all sources used, have been acknowledged in this thesis. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Candidate

Production Note:
Signature removed prior to publication.

(Fan Yang)
In loving memory of my father, Zengke Yang (1951-2013)
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ABSTRACT

In this thesis, a new microwave imaging technique for early stage breast cancer detection is developed to achieve two key aims: (i) to reconstruct the radar image of the suspicious region within the breast and (ii) to decide whether a suspicious region has malignant or benign tumors by differentiating their morphological features in terms of their complex natural resonances.

For our investigations we employ both numerical and chemical tissue mimicking breast phantoms. The breast phantom is illuminated by UWB pulses radiated from antenna elements arranged in a multistate configuration surrounding the breast. An efficient pre-processing technique is proposed to process the received pulses for the removal of early-time artifacts. To reduce the interferences of the background tissue clutter in inhomogeneous breast environment, a new time-of-arrival (TOA) auto-calibration is presented to estimate accurate TOA for confocal imaging. For determining the suspicious region within the breast, a novel and efficient data independent beam former known as Modified Weighted Delay and Sum (MWDAS) algorithm has been proposed. Once the suspicious region is localized by MWDAS method, the waveform of late-time backscattered field will be estimated using a proposed two-stage waveform estimation method. The accuracy of the waveform improves the extraction of complex natural resonances (CNR) that will be used to discriminate of whether a suspicious tissue is malignant or benign. Basing on radar target discrimination, we propose that the CNRs extracted from the late-time resonant tumor response can be closely related their morphological properties: spiculated lesion has CNR poles that differ from CNR poles of a smooth lesion. To validate our proposal, we perform FDTD simulations on 2D and 3D numerical breast phantoms that have been developed based on MRI-derived tissue dielectric properties. These simulations have revealed that the CNRs from malignant tumors have significant lower damping factors than the benign ones. These simulation
results helped to reconfirm that it is possible to distinguish malignant and benign breast tumors based on their CNRs.

To validate the proposed method of tissue discrimination, we have developed an experimental UWB imaging prototype using novel UWB sensors and tissue mimicking chemical breast phantoms to carry out preliminary preclinical experiments. Three novel end-fire compact sized UWB antennas have been proposed. After thoroughly investigating their characteristics, a novel UWB horn antenna known as BAHA that offered superior UWB performance is chosen, fabricated and measured to confirm its characteristics. A prototype experimental imaging system that incorporates 32 BAHA antenna elements forming a hemispherical UWB array is fabricated and tested using a vector network analyzer. Tissues mimicking chemical phantoms with dielectric properties similar to human breasts have been manufactured to have both adipose-tissue dominated homogeneous phantom with a dielectric contrast of 4:1 and a low-adipose inhomogeneously dense phantom with dielectric contrast of 1.7:1. Experimental results obtained using the hemispherical array prototype and phantoms have shown that dielectric inserts (12mm diameter) that mimic malignant and benign lesions can be successfully detected from both high and low dielectric contrast scenarios. Tumor mimicking lossy dielectric inserts with both irregular and smooth patterns have also been fabricated using chemicals to represent malignant and benign tumors respectively.

Finally, measured data from experimental prototype have demonstrated that tissue shape can be discriminated via CNRs. The experimental results confirmed that the proposed UWB antenna array is capable of picking up undistorted late-time signals from embedded tumor-mimicking dielectric inserts with different morphological profiles to offer reliable CNR extraction. Matrix Pencil Method is employed to extract CNRs from late time responses. Our investigations have confirmed that damping factors of the extracted CNRs from both spiculated and smooth inserts can be used to
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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{ij}(t)$</td>
<td>Received raw data between $i$th to $j$th antennas</td>
</tr>
<tr>
<td>$</td>
<td></td>
</tr>
<tr>
<td>$r$</td>
<td>Confocal point used in confocal microwave imaging</td>
</tr>
<tr>
<td>$H$</td>
<td>Complex conjugate transpose</td>
</tr>
<tr>
<td>$W_{BF}$</td>
<td>Beamforming weight</td>
</tr>
<tr>
<td>dia</td>
<td>diameter</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>Time interval used in FDTD simulation</td>
</tr>
<tr>
<td>$a(\theta)$</td>
<td>Steering vector of a narrow band signal</td>
</tr>
<tr>
<td>$\theta$</td>
<td>The angle at which an incident narrow band signal arrive at antenna array</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Wavelength</td>
</tr>
<tr>
<td>$\varepsilon_r$</td>
<td>Permittivity</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Conductivity</td>
</tr>
<tr>
<td>$E$</td>
<td>Expectation</td>
</tr>
<tr>
<td>$G$</td>
<td>Array gain</td>
</tr>
<tr>
<td>$\sigma^2$</td>
<td>Signal power</td>
</tr>
<tr>
<td>$R$</td>
<td>Cross-spectral density matrix</td>
</tr>
<tr>
<td>$\partial$</td>
<td>Constraint parameter on steering vector</td>
</tr>
<tr>
<td>$\prod_{i=1}^{M} x_i$</td>
<td>Product over $x_i$ from $i$ to $M$</td>
</tr>
<tr>
<td>$S_m$</td>
<td>$m$th s-plane CNR pole</td>
</tr>
<tr>
<td>$Z_m$</td>
<td>$m$th z-plane CNR pole</td>
</tr>
<tr>
<td>$\alpha_m$</td>
<td>$m$th damping factor of CNR</td>
</tr>
<tr>
<td>$f_m$</td>
<td>$m$th resonant frequency of CNR</td>
</tr>
<tr>
<td>$C_m$</td>
<td>$m$th complex amplitude of CNR</td>
</tr>
<tr>
<td>std(·)</td>
<td>Calculate the standard deviation of focused region</td>
</tr>
<tr>
<td>$\mu$</td>
<td>TOA compensation factor</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Constrain parameter to terminate the process of TOA autocalibration</td>
</tr>
<tr>
<td>$\beta_{\text{MMSE}}$</td>
<td>Scaling parameter used in minimum mean-square-error beamforming</td>
</tr>
<tr>
<td>$n_{\text{norm}}$</td>
<td>Normalized CNR error</td>
</tr>
<tr>
<td>$F$</td>
<td>Antenna fidelity</td>
</tr>
<tr>
<td>$S_{11}$</td>
<td>Reflection coefficients</td>
</tr>
<tr>
<td>$S_{21}$</td>
<td>Transmission coefficients</td>
</tr>
<tr>
<td>$e_c$</td>
<td>Antenna coupling efficiency</td>
</tr>
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</table>
## List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>BAHA</td>
<td>Balanced antipodal horn antenna</td>
</tr>
<tr>
<td>BAVA</td>
<td>Balanced antipodal Vivaldi antenna</td>
</tr>
<tr>
<td>CMI</td>
<td>Confocal microwave imaging</td>
</tr>
<tr>
<td>CNR</td>
<td>Complex natural resonances</td>
</tr>
<tr>
<td>CPML</td>
<td>Convolutional perfectly matched layer</td>
</tr>
<tr>
<td>DAS</td>
<td>Delay-and-sum</td>
</tr>
<tr>
<td>DCIS</td>
<td>Ductal carcinoma in situ</td>
</tr>
<tr>
<td>DFT</td>
<td>Discrete Fourier transform</td>
</tr>
<tr>
<td>DMAS</td>
<td>Delay-multiply-and-sum</td>
</tr>
<tr>
<td>FDTD</td>
<td>Finite-Difference Time-Domain</td>
</tr>
<tr>
<td>GPR</td>
<td>Ground penetrating radar</td>
</tr>
<tr>
<td>iFFT</td>
<td>inverse Fast Fourier Transform</td>
</tr>
<tr>
<td>IDAS</td>
<td>Improved delay-and-sum</td>
</tr>
<tr>
<td>LCIS</td>
<td>Lobular carcinoma in situ</td>
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<tr>
<td>MAMI</td>
<td>Multistatic adaptive microwave imaging</td>
</tr>
<tr>
<td>MIST</td>
<td>Microwave-imaging-via-space-time</td>
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<tr>
<td>MWDAS</td>
<td>Modified-weighted-delay-and-sum</td>
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<tr>
<td>MMSE</td>
<td>Minimum mean-square-error</td>
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<tr>
<td>MPM</td>
<td>Matrix pencil method</td>
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<tr>
<td>MVDR</td>
<td>Minimum variance distortionless beamformer</td>
</tr>
<tr>
<td>NFD</td>
<td>Near field directivity</td>
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<tr>
<td>NCR</td>
<td>Normalized CNR error</td>
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<tr>
<td>PEC</td>
<td>Perfect electric conducting</td>
</tr>
<tr>
<td>PML</td>
<td>Perfectly matched layer</td>
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<tr>
<td>RCB</td>
<td>Robust capon beamforming</td>
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<tr>
<td>RCS</td>
<td>Radar cross section</td>
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<tr>
<td>RMSE</td>
<td>Root-mean-square-error</td>
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<tr>
<td>SCB</td>
<td>Standard capon beamforming</td>
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<tr>
<td>SEM</td>
<td>Singularity expansion method</td>
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<tr>
<td>SNR</td>
<td>Signal-to-noise ratio</td>
</tr>
<tr>
<td>SCR</td>
<td>Signal-to-clutter ratio</td>
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<tr>
<td>TOA</td>
<td>Time-of-arrival</td>
</tr>
<tr>
<td>TG-RCB</td>
<td>Transmitter grouping robust capon beamforming</td>
</tr>
<tr>
<td>TSAR</td>
<td>Tissue sensing adaptive radar</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>--------------------------------------------</td>
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<tr>
<td>UWB</td>
<td>Ultra-wideband</td>
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<tr>
<td>UWCEM</td>
<td>University of Wisconsin Computational</td>
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<tr>
<td></td>
<td>Electromagnetics Laboratory</td>
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<tr>
<td>VNA</td>
<td>Vector network analyzer</td>
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