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Ubiquitous Applications of Microwave Imaging Techniques and their Feasibility

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Abstract— Microwave imaging techniques have shown excellent capabilities in various fields such as civil engineering, nondestructive testing, industrial applications, and have in recent decades experienced strong growth as a research topic in biomedical diagnostics. This papers aims to amalgamate the various techniques used for microwave imaging and deep study on their feasibility.

I. INTRODUCTION

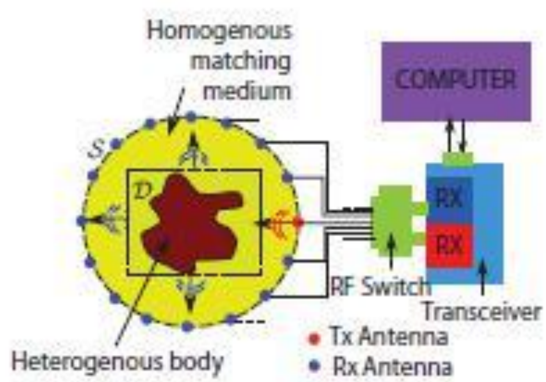
Microwave imaging is an imaging technique which uses non-ionizing electromagnetic (EM) signals in the frequency ranging from few hundreds of megahertz to few gigahertzes. It is an emerging technique in various fields such as medical imaging, antenna synthesis, electromagnetics, and component design. Microwave imaging for medical applications started as a feasibility study by imaging organs as a perfused canine kidney by Larsen and Jacob in 1980s.

The penetration through opaque medium makes microwaves a convenient agent for non-invasive testing, evaluation and measurements. Medical imaging is usually done to visualize the interior of the body of both healthy and diseased subjects. These images of the body are considered for clinical analysis and detection of any abnormalities. On the contrast from medical applications microwave imaging techniques can be used for the retrieval of information about unknown conducting/di-electric objects scattered by external microwave sources, whose applications include civil and industrial engineering, non-destructive testing and geophysical prospecting.

II. DESCRIPTION & WORKING

Microwave Imaging Setup

It consists of several antennas located around the body to be imaged. The antenna can form a 3D array. One antenna transmits at a time: it is connected to the transmitter and the scattered signal from the body is collected by the rest of the antennas that are connected to the receiver. Usually, there is an RF switch, that quickly switches between different antennas, such that all or some antennas act as a transmitter while the rest of the antennas are connected to the receiver. Between the antennas and the body, there is a homogeneous matching medium. The matching medium helps in reducing the reflections by coupling the signal to the body. This is because of the fact that, in the absence of the matching medium, a high reflection may occur between the tissue and the medium, which is the air in which the antenna system is kept. This would result in a weak signal that could penetrate the body. Hence, matching medium helps in reducing this reflection, and a relatively higher strength of the signal can penetrate the body. A simple matching medium that has been used is water. After the scattered signal is collected by the antenna and processed by the receiver to get meaningful signal data, the data are transferred to a computer. The computer executes the imaging algorithm to generate the image of the body. By the analysis of the generated image, the required qualitative or quantitative properties of the body can be fetched.



Basic setup for microwave imaging in a two-dimensional case when one antenna (TX) transmits the signal and all other antennas (RX) are in receiving mode. The imaging domain _ contains the heterogeneous body to be imaged. The measurement domain contain the transmit and the receive antennas. The whole system is in a homogeneous medium that acts as a matching medium. The RF switch switches between different antennas, such that all or some antennas acts a transmitter while the rest of the antennas are connected to the receiver. The transceiver is connected to a computer to which the collected signal data is transferred. The computer also executes the imaging algorithm.

III. MICROWAVE IMAGING ALGORITHMS

Quantitative Imaging Algorithms

Quantitative imaging is also called tomography. The microwave tomography problem is formulated in terms of electric fields. To formulate the problem, two domains are defined: bounded domain $(\mathcal{D})$ and the measurement domain $(\mathcal{S})$. The bounded domain is a domain in which the body to be imaged is enclosed. The antennas are located on the measurement domain. These are shown in Figure 19.2. Three electric fields are defined for the purpose: the incident field E^{inc} on $\mathcal{D}$, the total field E^{total} in $\mathcal{D}$, and the scattered field E^{scatt} on $\mathcal{S}$. A time harmonic dependence $\exp(j\omega t)$ with $j^2 = -1$, and $\omega = 2\pi f$ where f is frequency, is assumed. The scattered field on $\mathcal{S}$ is defined by the following *data equation:*

$$E^{scatt}(\mathbf{p}) = k_b^2 \int_{\mathcal{D}} \mathcal{G}(\mathbf{p}, \mathbf{r}')\chi(\mathbf{r})E^{total}(\mathbf{r})dv(\mathbf{r}'),$$

where:

$\mathbf{p} \in \mathcal{S}$, $\mathbf{r}'$, and $\mathbf{r}$	are position vectors
k_b	is the wavenumber of the matching medium
$\mathcal{G}$	is the Green's function that has a different expression for transverse magnetic (TM), transverse electric (TE), or 3D full vectorial case illumination [32]
$\chi(\mathbf{r})$	is the contrast function containing the permittivity $(\mathbf{r})$ of the body in a matching medium with the permittivity ε_b and is defined as:

$$\chi(r) = \frac{\varepsilon(\mathbf{r}) - \varepsilon_b}{\varepsilon_b}.$$

The total electric field E^{total} satisfies the *domain equation* in $\mathcal{D}$:

$$E^{total}(\mathbf{r}) = E^{inc}(\mathbf{r}) + k_b^2 \int_{\mathcal{D}} \mathcal{G}(\mathbf{r}, \mathbf{r}')\chi(\mathbf{r}')E^{total}(\mathbf{r}')dv(\mathbf{r}').$$

The objective is to determine the contrast by solving these two equations. This is a nonlinear and ill-posed inverse EM scattering problem. Hence, the best way to solve them is through iterations where the domain $\mathcal{D}$ is discretized into N cells or pixels. In each of these pixels, the electrical properties are assumed to be constant. Many quantitative reconstruction algorithms have been developed [31]. These can be further categorized into two groups depending upon the cost-function used. These are either Newton-type iterative algorithms [32,33–39] or Modified Gradient (MGM) [40,41] and Contrast Source Inversion (CSI) algorithms [42]. The cost-function for the Newton-type algorithms is of least square type as:

$$C_{Newton} = \frac{\sum_t \left\| E_t^{scatt} - E_{meas,t}^{scatt} \right\|_S^2}{\sum_t \left\| E_{meas,t}^{scatt} \right\|_S^2},$$

where:

The summation is done over the transmit antennas

$E_{meas,t}^{scatt}$ is the computed scattered field at all the receiver antennas, from the data and the domain equations for a particular transmit antenna t

$E_{meas,t}^{scatt}$ is the measured scattered field for that transmit antenna

A. Advantages

From the medical applications perspective of all the internal imaging procedures available to physicians, the CT scan is the most detailed, and can give a doctor the most complete picture of what's happening inside a patient's body. They are particularly useful and widely used in diagnosing cancer.

The principle advantages of quantitative imaging algorithms are:

- Rapid acquisition of images.
- A wealth of clear and specific information.

B. Disadvantages

Once again from the medical applications perspective, compared to other diagnostic tests, CT scans deliver a relatively high dose of radiation to the patient. While this is not usually a problem for a single scan, patients who need to undergo repeated tests can be subjected to a significant level of radiation, increasing their cancer risk.

- A view of a large portion of the body.e principle advantages of quantitative imaging algorithms are:

- Rapid acquisition of images.
- A wealth of clear and specific information.

- A view of a large portion of the body.

Qualitative Imaging Algorithms

In general, quantitative algorithms are computationally and memory-wise demanding. Moreover, in some applications such as in breast cancer detection, the main objective is not to know the electrical properties of the tissues, but to determine the existence and location of the tumour. In such cases, qualitative imaging algorithms can be used. Qualitative imaging algorithms are similar to radar-based algorithms where the objective is to detect strong scattering objects. In case of medical microwave imaging, the malignant or the tumorous tissue is a strong scatterer due to higher dielectric properties than the surrounding tissues. Various radar-based imaging algorithms to focus the tumour, such as confocal microwave imaging, beam forming , and tissue sensing adaptive radar are used. Ultra-wideband (UWB) signal is used for qualitative imaging to have a good time resolution. In qualitative imaging, each antenna transmits a short pulse at a time (UWB in frequency domain), and the backscatter response is received by the same antenna. The backscatter response consists of the tumour response, scatter from the skin, and backscatter from other tissues. Signal processing is used to reduce the effect of the skin and the backscatter from other tissue, to enhance the signal backscattered by the tumour. For example, in confocal microwave imaging, the processed backscattered waveform at each of the antennas is integrated over time to obtain B t integrated waveforms, where t is the number of the transmit antennas. The reconstructed image is then created by time-shifting and summing data points from these integrated waveforms for each synthetic focal point **r** in the imaged body. The intensity *I(* **r** *)* of a pixel in the image at **r** is the square of the coherently summed values:

$$I(\mathbf{r}) = \left[\sum_t c_t B_t(\tau_t(\mathbf{r}))\right]^2,$$

where:

$\tau_t(\mathbf{r}) = 2\lvert\mathbf{r} - \mathbf{r}_t\rvert / v\Delta T$	is the time delay from the tth antenna at $\mathbf{r}_t$ to the synthetic focal point at $\mathbf{r}$ in the body
υ	is the propagation velocity of the signal inside the body, assuming a homogeneous medium
c_t	are weights to compensate for the radial spreading of the cylindrical waves as they propagates outward from the transmit antenna

A. Advantages

From the industrial applications perspective such as RADAR signals can penetrate mediums such as clouds, fogs, mist and snow. The signals used by RADAR technology are not limited or hindered by snow, clouds or fogs. This means that even in the presence of these adverse conditions, data will still be collected.

- It can give the exact position of an object.
- It can determine the velocity of a target.
- It can measure the distance of an object.
- Easy data acquisition at different scales.
- Spot the difference between stationary and moving objects.

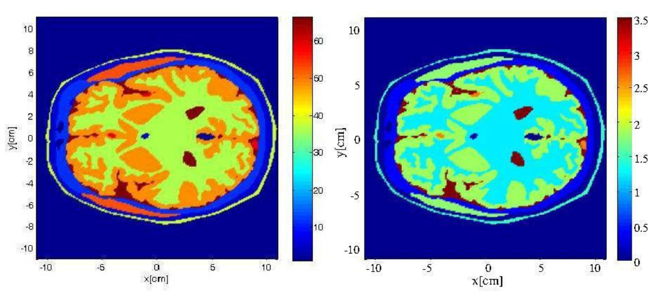
B. Disadvantages

Large objects that are close to the transmitter can saturate the receiver. The radio signals work best when the object is further away from the receiver and not closer. Readings may be falsified if the object is handheld. If the target is held in the hand, the data collected may not be accurate. It can be oversensitive and cannot be used beyond ionosphere.

IV. BIOMEDICAL APPLICATIONS

A. Brain Imaging

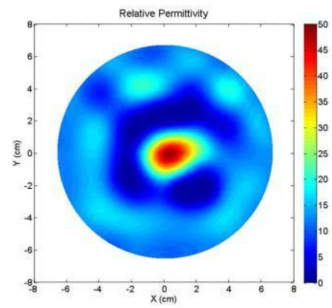
Microwave imaging of the brain can be done to detect and locate the area of the damaged brain tissues due to injuries or conditions such as ischemic or haemorrhagic stroke. A stroke may result in accumulation of a blood clot within the brain. As there is a difference between the electrical properties of the blood and normal brain tissues, microwave imaging can be used to detect the blood clot. Research reported in focus on such stroke detection in the brain using microwave imaging. Quantitative methods used so far include a Newton-type iterative scheme for 2D tomography, the born iterative method, and a multiplicative regularized Gauss-Newton inversion. Qualitative approach as confocal imaging has also shown to detect stroke.



(a) (b)

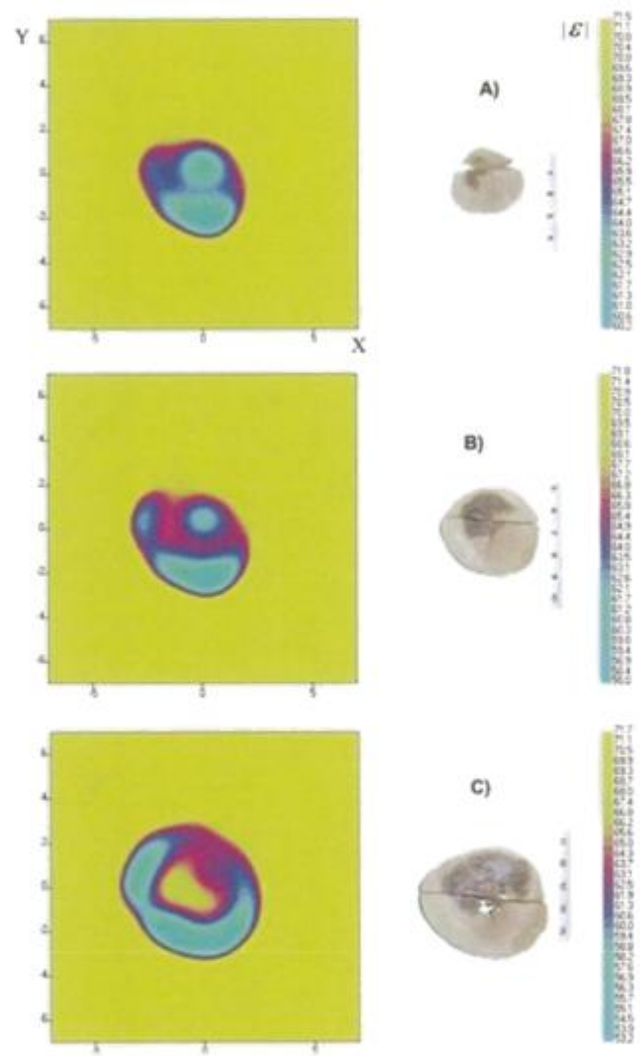
B. Breast Imaging

One of the most widely investigated medical applications of microwave imaging is detection of breast tumour. The breast tumour has relatively high contrast when compared with the prominent fat tissue in a breast making the tumour as a significant scattering. Hence, radar-based techniques can be effectively applied to locate the tumour, as reported in. The tomographic methods can also be used where the tumour can be distinguished easily from the rest of the fat tissues in the reconstructed image.



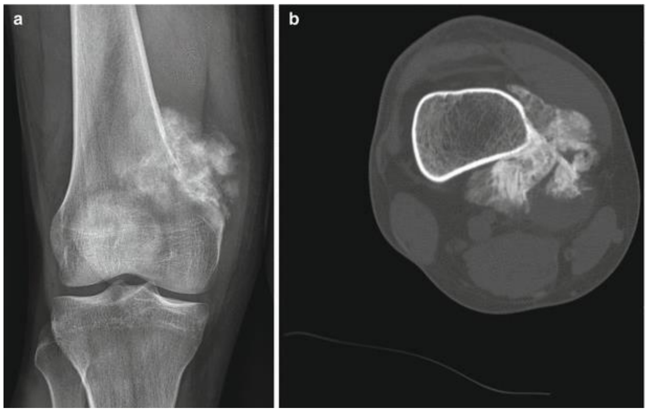
C. Heart Imaging

The objective of heart imaging using microwaves can be to detect any pathological conditions, such as myocardial infarction, as the dielectric properties of myocardial tissue have a strong dependence on coronary blood flow. It can also be used to obtain the temporal images of a beating heart for heartbeat extraction, due to millisecond temporal resolution of microwave imaging. The reconstructed quantitative images of an excised canine perfused heart in a static, as well as in a beating case.



D. Bone Imaging

Microwave imaging for bone has been done to detect leukaemia in the bone marrow. Another application that is reported is the determination of the bone density for detection of osteoporosis. Leukaemia causes the cellular population in the bone to increase, which, in turn, increases the relative permittivity and decreases the conductivity up to a factor of 2. Both of these applications require the electrical properties of the bone to be known, and, thus, quantitative approaches are used. The Levenberg-Marquardt method has been used for leukaemia detection and Gauss-Newton iterative method for the detection of osteoporosis.



V.LITERATURE REVIEW

The various techniques used in microwave imaging are discussed in this section.

A 2.45 GHz microwave camera was developed by Franchois etal [1] where they used method of moments combined with distorted Born iterative method for image reconstruction.

In microwave imaging algorithm developed by Sourov etal [2], the direct solution for the scattering problem was obtained by fast forward iterative method and inverse solution by Newton iterative method.

Chew etal [3] developed a time domain approach that incorporated the FDTD method in distorted born iterative method to the reconstruct images.

A microwave imaging system that operated at 2.45 GHz was developed by Joefre etal [4]. Phantoms having dielectric constants 45, 49, 46 and 32 with water as the coupling medium was considered. The image reconstruction algorithm was formulated in two dimensions using Born approximation. It was assumed that scattering acted as a small perturbation on the illumination and therefore the field within the body was approximated by the incident field.

The images were not good, due to the limitations of Born approximation [5] and due to the dielectric contrast between water and phantoms.

Meaney etal [6] Developed a dual mesh scheme for image reconstruction where the field variables were decoupled from the reconstruction parameters thereby minimizing the amount of observational data needed to recover electrical property profiles without sacrificing the quality of the reconstructed images.

The work was extended [7] using Newton's iterative scheme based on finite element (FE) representation, which was coupled with boundary element (BE) formulation for finding the forward solution of the electric fields. It utilized FE discretization of only the area of interest while incorporating the BE method to match the conditions of the homogeneous background region extending to infinity.

They also developed an active microwave imaging system [8] in the frequency range of 0.3 - 1.1 GHz and 2-D electrical property distributions of phantom were reconstructed using the above algorithm.

Multi target tissue equivalent phantoms [9] were also investigated in the same frequency range, using then same coupling media. In addition, low pass filtering was applied during the iterative reconstruction process by spatially averaging the updated reconstruction parameters at each iteration, which reduced the effects of noise and measurement imprecision. The electrical properties were found to be frequency dependent and an error of -50% was reported for a dielectric constant variation of 10 - 20% between the phantom and the background medium.

The same group modified the hybrid element strategy by modifying the forward solution problem in microwave tomographic imaging [10]. The electric fields were calculated at each iteration and the Jacobian matrix calculations were updated with the new electrical property values.

They also performed ex-vivo microwave imaging experiments in normal breast tissue sample with salineminclusion, immersed in saline [11]. Due to the contrast between the breast tissue and the saline, the reconstructed images were not clear. Single object investigations were performed to isolate the 3-D effects without additional perturbations from scattering interactions from multiple targets.

The hybrid element approach was further explored [12-13] where finite element method was deployed inside the biological imaging region of interest. The 2-D Microwave Tomographic Imaging electromagnetic property distribution was expressed in a piecewise linear basis function expansion whose coefficients were to be consisted of the attenuating medium containing the electromagnetic radiators was discretized using boundary element method.

Same group realized a water coupled prototype microwave imaging system [14] to perform multislice examinations of the breast over a broad frequency range of 0.3 - 1 GHz. Hybrid element approach was used for image reconstruction.

The obtained relative pennittivities of the breast tissues were considerably higher than those previously reported [15].

They also studied the 3-D effects in 2-D microwave imaging using a wide range of phantom and simulation experiments [16].

The frequency range is enhanced to 0.5 - 3 GHz by developing a parallel detection microwave system for breast imaging [17].High quality reconstructions of inclusions embedded in phantoms were achieved up to 2.1 GHz.

Conformal microwave imaging algorithm for breast cancer detection was investigated by Li etal [18]. They used Gauss-Newton iterative scheme for microwave breast image reconstruction where the heterogeneous target zone within the antenna array was represented using finite element method while the surrounding homogeneous coupling medium was modelled with boundary element method.

Slaney eta! [19] developed a microwave imaging algorithm by relating Fourier transformation of projection views to samples of two-dimensional Fourier transformation of the scattering object. They also discussed the limitations of first order Born and Rytov approximations in scalar diffraction tomography.

Tseng etal [20] simulated quasi monostatic microwave imaging using multi source illumination. The object rotation angle was reduced but multiple sets of the object Fourier domain data were received from multiple sources at the same time.

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