MÄLARDALEN UNIVERSITY

Microwave Imaging of Biological Tissues

Research Planning Course

Assignment 2: Research overview of Related Research

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1 Introduction

1.1 Research area

Microwave imaging can be defined as seeing the internal structure of an object by illuminating the object with low-power electromagnetic fields at microwave frequencies that is between 300MHz – 300GHz. A transmitter sensor (typically an antenna) is used to illuminate the object with microwaves, which travels through the object and is then detected with receiver antennas at the other side of the object. Another technique is to use reflections, which are detected with the same transmitter that is illuminating the object. Thus microwave imaging can be divided into two approaches namely the transmission-reflection approach, which is used in our research, and the other is reflection or radar technique. The measured data can be processed using reconstruction algorithm to give information on the complex dielectric permittivity of the scattering object.

Microwave imaging for medical applications is of big interest nowadays. The imaging with microwaves allows nondestructive evaluation of biological tissues. Changes in the dielectric properties of tissue can be related to their physiological condition. There has been proposed several applications of microwave imaging in the biomedical field and one of them are microwaves for breast tumour detection. The contrast in permittivity for different in-vivo tissues (fat, bone, malign tumour, vascular tissue etc.) is much higher for microwaves than the most successful tool used today X-ray Computed Tomography (CT) is able to produce. For this reason microwave imaging has been developed as a complementary modality to mammography. However, microwave imaging techniques, needs a lot of improvement in both hardware (antenna, electromechanical parts and RF-design) and in the software (imaging algorithms) to be considered as a reliable modality for biomedical application. The most encouraging results to date have been obtained by Meaney *et al.*, Semenov *et al.* and Bolomey *et al.* with promising potential for the further development of microwave imaging of biological tissue.

1.2 Project

The research in our group is to investigate the usage of microwaves as a possible imaging method in biomedicine, which means to develop a system for concept studies for microwave imaging modalities in biomedicine. In our first studies we concentrate on using microwave imaging for breast tumour detection. But results from this research could possibly be useful in other applications in biomedicine or even in other areas such as industry.

Developing a microwave imaging system is a wide knowledge problem, which may be divided into three parts:

- The characterization of dielectric properties (complex permittivity) of human tissue
- Antenna and RF hardware design
- Algorithm development with physical models of the electromagnetic fields and material properties

My research is concentrated mainly on the first two parts with some reflections on the algorithm. And the method that I have used to determine the complex permittivity, the dielectric constant and loss factor, is the resonant cavity perturbation method. The theoretical and experimental results will be confirmed by using the FDTD simulator to analyze the model behaviour.

Further the hardware design has been planned in broad outlines and with the algorithm development we will hopefully have a complete system for microwave imaging at Mälardalens University. This will make a contribution on active research in microwave imaging, which will position our research among the other microwave imaging groups in the world.

1.3 Method

For the system design the idea is to use an available industrial ABB robot on which arm a receiving antenna matrix should be detached. The center point of the antenna matrix will be programmed so that it could move along a surface of a half cylinder in cylindrical coordinates and a half sphere in spherical coordinates around the examination objects. The half cylinder and half sphere positions will be determined with the use of a parameter that indicates the transmitting antenna's position and the radius of the cylinder or sphere. The examination object and the antenna matrix will be immersed in a container filled with a floating coupling medium i.e. water with different values of the complex permittivity. This is done to approximate the dielectric properties of the medium to those of the object in order to minimize reflection. Therefore a study on different types of antennas and their behavior in other mediums than air, such as water will be performed to find the appropriate antenna for the system. With the first conceptual studies it is planned to reconstruct 2-D images having in mind a possibility for 3-D imaging system in the future. The object to be examined in the first attempt is a so called phantom and this is an object which reconstructs certain quantities of real tissue.

In order to determine the correlations between tissue dielectric properties and its physiological state a phantom has to be developed. Then the characterization of dielectric properties of human tissue becomes very important in the microwave region and a method for complex permittivity measurement must be investigated. Another important issue is to have precise control of the complex permittivity in the background media (water) in our chamber (container).

A widely used method to determine the complex permittivity, the dielectric constant and loss factor, is the open-ended coaxial probe technique. But the high price of this probe and inability to use the measurement for creating reference values, require a complementary technique both cheaper and more accurate. The decision was to use resonant cavity perturbation method. The sample to be studied is introduced into a resonant cavity in a suitable way and its complex permittivity is determined from the change of resonant frequency and quality factor of the cavity. Promising results have been obtained for fresh water, distilled water, 1.2-propylene glycol, on a breast phantom with a tumor implemented and finally on human blood sample (my own).

2 Research Overview of Related Research

Previous research of microwave imaging of biological tissue with the leading research groups will be described briefly and summarized, beginning with the work by Larsen and Jacobi in the early 80s until the work and hot topics that has been done by the leading research groups today. The hardware developing is the main area of my research so I will focus on that and point out the relevance for, and relation to, my work.

Various hardware setups have been developed during the last three decades. The first successful hardware setup was made by Larsen and Jacobi in the early 80's, which resulted in images showing the internal structure of canine kidneys. These experiments where done by using two antennas with a mechanical rotation around the object and measuring the transmission coefficients between them [1]. Even though this paper is from 1979 almost every leading microwave imaging group is referring to it, so the paper could be treated as a seminal paper. These results are historical and they established the future of microwave imaging of biological tissues.

2.1 The Planar Microwave Camera

Another hardware setup is the planar microwave camera at Supeléc in Paris developed by Bolomey *et al*. this planar microwave camera is constructed by two horn antennas, one transmitter and one receiver. In the front of the receiving antenna a matrix of 32x32 =1024 sensors (dipole antennas) are used, a so called Modulated Scattering Technique (MST), to enable a quick data acquisition.

This is a quite simple hardware because the sensors only use a frequency of 200 kHz and modulates the planar carrier wave frequency of 2.45GHz [2]. The main goal with the planar microwave camera was to produce qualitative images of the temperature distributions of biological tissues to control the effect during hyperthermia treatment [3]. The camera has been further developed since then to produce quantitative results [4] as well as qualitative results in a quasi real-time manner [5]. Alain Joisel has developed the real-time functionality of the system with results that have been reported with a rate of 25 images/s [5]. Tommy Gunnarsson has done improvements in the algorithm, which was developed for this camera by Nadine Joachimowicz, where he obtained simulated results with a 2D Newton-Kantorovich algorithm for a multi-view planar configuration.

The receiving sensor antenna of the planar microwave camera using the Modulated Scattering Technique, the so called “retina”, is a hardware design that we have considered to use in our research and development of the microwave camera prototype at Mälardalens University.

2.2 Circular Microwave Imaging

2.2.1 Two Dimensional System for Biological Imaging

Semenov *et al.* developed a 64 antenna circular microwave imaging system using waveguide antennas, divided into 32 emitters and 32 receivers, operating on frequency 2.45GHz [6]. With this system the group produced reconstructed a systolic and diastolic image of the beating canine heart and the total acquisition time was less than 500 ms. The antennas are located on the boundary of the cylindrical chamber filled with various solutions including distilled water. The waveguide antennas are constructed with a three time wider field pattern in the horizontal plane compared to the vertical plane. This adjustment was done to try if it was possible to use a 2-D diffraction model and create 2-D images slicing a 3-D object similar to the X-ray tomography technique. Their conclusion and suggestion where, to reconstruct a quantitative 3-D object it is necessary to have a 3-D system, so the “slice” technology used in X-ray tomography could not be used. Another important conclusion is the use of a multi frequency system where an optimal range is between 0.9 and 3 GHz for microwave imaging.

2.2.2 The clinical prototype for active microwave imaging

Similar to Semenov *et al.* Meaney *et al.* developed a circular microwave imaging system for reconstruction of 2-D electrical property distributions. In the first setup they also used waveguides antennas (four) for transmitting, but monopole antennas (four) for the receiver. The system operates on frequencies between 300-1100 MHz [7].

A multi frequency system is something that our research group is considering to use. And the motivation is that the system could be used in an experimental research to see which frequency is the optimal for the imaging. Another improvement using multi frequencies is that it produces more data, which could result in a better image quality and for sure it improves the system's functionality.

Meaney *et al.* were the first to develop a clinical prototype for active microwave imaging of the breast in the early 2000's [8]. The hardware has been design to have each antenna operate in either transmit or receive mode. In this case they used 16 monopole antennas in a circular array configuration and a reason for using the monopole antennas is that the monopole can be effectively modelled as a line source in a 2-D imaging problem. Another advantage is that, even if monopole antennas typically show undesirable characteristics when operating in a lossless medium (narrow bandwidth and excitation of surface waves), they are excellent radiators in a lossy environment where the usable bandwidth is increased with no evident excitation of surface currents. The purpose of this system is to detect early stage breast tumours with quantitative images. The system is based on the earlier system where they have mounted the system on a transportable bed with hole for breast insertion. This study has been preformed on real patients with different ages and breast images of 5 patients have been obtained. The initial results gave sliced 2-D images of the human breast with a reasonable resolution. One important thing that the group is mentioning in this setup is to model each nonactive antenna as a microwave sink so the entering signals (E-field) are absorbed and not re-radiated. In the hardware they have selected to use matched switches so when an antenna is in the nonactive state any coupled signal is transmitted through a coaxial cable into the switch with a matched termination without being re-radiated.

Over the last few years many improvements have been done on the system's software [9, 10], while using the same hardware. And today one could say that this system is the state of the art regarding microwave imaging for breast cancer detection.

The monopole antenna array mentioned above is another antenna design, beside the retina, that is relevant as a sensor for our microwave imaging system.

2.3 Three-dimensional Microwave Imaging

2.3.1 The first system by Semenov *at al.*

Semenov *at al.* have also performed experimental 3-D microwave imaging studies. They developed two different systems for those studies [11, 12]. The first system is constructed on a non-metallic cylindrical chamber with use of 32 waveguide antennas in a vertical array of transmitters and a single waveguide antenna of same type for the receiver and the operating frequency for the system is 2.36GHz [11].

The waveguide antennas are built to match the bolus medium, in order to reduce the return loss, by filling the antenna with barium titanate (that has a dielectric constant ε'=60). Another advantage with this antenna design is that the size of the antenna is minimized (1x0.5 cm) which result in a shorter antenna than a wavelength (1.5 cm). These make it possible to model the waveguide antenna as a dipole antenna and reduce the complexities in the imaging calculation process.

To create the measurement an electromechanical system is used where the transmitting antenna array is fixed and the object is rotating while the receiving antenna is collecting the scattered field data. The data acquisition process in this system is time consuming, they improve it by using a code division technique but it still takes 8 hours to perform one measurement with 32 directions on a 3-D object [11].

2.3.2 The second system by Semenov *at al.*

The second system for 3-D microwave imaging by Semenov *et al.* is built around a larger metallic chamber and the transceiver part differ from the previous described system, namely it uses a network analyzer as a transmitter and receiver [12]. In this system only two waveguide antennas are used similar to those in the first system and they are tuned to frequencies between 0.8 and 1GHz. This is comparable to our system where we intend to use the network analyzer as a transceiver but not the waveguide antennas as sensors. The waveguide antennas are set on two different arms and with a robotic system under computer control they are positioned at various points inside the chamber while the object is fixed in the middle of the chamber. Both antennas can be rotated individually under the data acquisition, which makes it possible to measure the components (vertical and horizontal) of the electromagnetic field. The electromechanical part of the system requires high accuracy and stability because the data acquisition time is approximately 9 hours. These requirements are realized using accurate microwave and electronic components and optoelectronic control of mechanic position of antennas. However there is still some instability in the technical parameters due to the long data acquisition time, but more critical is the physiological instability of the object and the coupling solution inside the chamber, which are the main reasons for the limited image quality. Another limitation of the image quality is the inadequacy in the mathematical model of the tomography experiment. Regardless of these limiting factors the group obtained images of a full size canine and that is an important milestone in the progress of microwave imaging.

The accuracy and stability of the systems electromechanical parts are important factors that our group has been considering while planning the systems hardware design. So using an industrial ABB robot would hopefully give us a stable system with accuracy of some tenths of a millimeter. Another benefit using the robot is great improvement in data acquisition time. With these conceivable parameter improvements significant sources of error might be removed and the performance of the electromechanical parts of the system would be secured.

2.4 Microwave imaging via space-time beamforming

All mentioned research groups above use the transmission-reflection technique for development of their microwave imaging systems. Another significant group in the research area is Hagness *et* al., which use techniques based on radar technology, such as beamforming, for microwave imaging. The group is attempting to detect breast cancer using reflections to form images [13]. This method is not considerable for the system development in my research project so only a brief study has been done to select out the relevant issues, which are the breast phantom development and the material for the coupling medium between the breast phantom and the antenna. The base material for the breast phantom is soybeans, the skin layer is modeled with a thin (1.5 mm) printed circuit board and the tumor is reproduced by a diacetin–water solution. The coupling (background) media is soybean oil.

2.5 The Phantom Development

In our project, phantoms have to be designed to reconstruct the dielectric properties of human tissues. The dielectric property of human tissues varies with frequency and it can be difficult, or almost impossible to find existing tailor-made materials, which have the same frequency dependence as the needed tissue. Gabriel *et al.* have put together two papers representing the complex permittivity, the dielectric constant (real part) and the conductivity (imaginary part), of various biological tissues in graphical format [14, 15]. The first paper is a review of all the main biological tissues for which there are three or more literature reports [14]. In this article data of the complex permittivity at different temperatures are presented as a function of frequency. The second paper is an experimental investigation of the dielectric properties of biological tissues in the frequency range from 10 Hz to 20 GHz [15]. The measurements were performed using automatic swept frequency network and impedance analyser. Comparing the result with corresponding data from the literature shows good agreement.

2.6 Literature

The main sources of knowledge regarding microwave imaging are the publications written by the leading research groups mentioned in this report and their references. I have tried to pick out and present the most relevant articles from these research groups for my research. In addition to the relevant publications there are many obligatory theory books used as a reference literature which are based on electromagnetic field theory, antenna theory, microwave engineering, applied physics and mathematical books both theory mathematics and mathematical techniques for engineering problems literature.

For the permittivity measurements I have used the books “Time-Harmonic Electromagnetic Fields” by Roger F. Harrington [16], and “Advanced Engineering Electromagnetics” by Constantine A. Balanis [17] both books containing topics of advance electromagnetic field theory and analysis of electromagnetic phenomena. Chapters describing waveguides, cavities and perturbation and variation techniques have been studied in depth. Also a few publications are used as support for the permittivity measurement study [18, 19, 20].

3 Cooperation

Microwave imaging for biomedical applications is not yet a ready imaging technique for clinical use only experimental prototypes have been designed, so collaboration with the medical industry is not of interest at the moment. But our group has started an academic collaboration with one of the leading research group in the microwave imaging field, namely the Paris group at Supélec with professor Bolomey leading the research. This is a good opportunity to expand the microwave imaging with a few more groups, it should at least be five, to start an EU microwave vision project group and then the possibility to cooperate with the big industry players like Siemens and General Electric becomes more realistic.

4 Key conferences

Specific microwave imaging conferences do not exist, but there are several others that can be thinkable as potential key conferences and could be found under the following societies.

IEEE Antennas and Propagation Society has a focus on experimental and theoretical advances in antennas including design and development. Concerning the word "propagation" it relates to propagation of electromagnetic waves including: scattering, diffraction and interaction with continuous media. Applications relevant to antennas and propagation are such as remote sensing, applied optics, and millimeter and submillimeter wave techniques. Among the topics of interest on the next conference are biomedical imaging and biomedical applications.

IEEE Microwave Theory and Techniques Society (MTT-S) is a transnational society that supports the advancement of microwave theory and its applications, including: RF, microwave, millimetre-wave and terahertz technologies.

IEEE Circuits and Systems Society has a field of interest in: the theory, analysis, design (computer aided design), and practical implementation of circuits. Under this society there is an interesting and relevant journal for my research, the new IEEE journal called IEEE Transactions on Biomedical Circuits and Systems and it covers circuit and system design issues in a wide range of applications found in biomedical sciences.

IEEE Instrumentation and Measurement Society is dedicated to the development and use of electrical and electronic instruments and equipment that is capable to measure, monitor and record physical phenomena. The fields of interest relevant for my research are systems and standards for measuring and recording electrical quantities in frequency and time domains, instrumentation for measurement of non-electrical variables and calibration.

IEEE Engineering in Medicine and Biology Society fields of interest are: "The application of the concepts and methods of the physical and engineering sciences in biology and medicine. This covers a very broad spectrum varying from formalized mathematical theory through experimental science and technological development to practical clinical applications." The worlds leading research groups in the microwave imaging field have published their work in a journal from this society, namely the IEEE Transactions on Biomedical Engineering journal.

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Microwave thermoelastic imaging uses microwave-pulse-induced thermoelastic pressure waves to form planar or tomographic images.Â It discusses the science of thermoelastic wave gen-eration and propagation in biological tissues; the design of prototype microwave thermoelastic tomographic imaging (MTTI) systems; and the reconstruction of tomographic images using ltered-back projection algorithms; as well as the per-formance of prototype microwave thermoelastic tomographic systems in phantom models and human subjects. In present work we compare microwave images of the biological tissue phantom with several inclu-sions at three frequency ranges: 5.6â€"6.6, 14â€"15 and 20â€"22 GHz with the frequency step of 0.2 GHz. The phantom was made of the pig fat tissue imitating human breast fat tissue (relative permittivity Îµ â‰ˆ 5). Scheme of the phantom is given in Fig. 1. Phantom contains six dielectrically contrast inclusions: three of them were made of material imitating tumor (Îµ â‰ˆ 40) of 10 mm diameter each and three metal balls with diameters 14, 10 and 6 mm. Home Search Collections Journals About Contact us My IOPscience. Optical properties of biological tissues: a review. This article has been downloaded from IOPscience. Please scroll down to see the full text article.Â Abstract A review of reported tissue optical properties summarizes the wavelength-dependent behavior of scattering and absorption. Formulae are presented for generating the optical properties of a generic tissue with variable amounts of absorbing chromophores (blood, water, melanin, fat, yellow pigments) and a variable balance between small-scale scatterers and large-scale scatterers in the ultrastructures of cells and tissues. (Some gures may appear in colour only in the online journal). Introduction. Microwave and millimeter-wave reflectometry is one of the potential techniques for the diagnosis and detection of biological abnormalities, such as subcutaneous masses or cancerous tumors in human body. In this paper, a high-quality microwave sensor based on planar misrostrip resonator is designed, fabricated, and successfully tested with different kinds of biological samples. The proposed sensor has unique properties such as small size, simple fabrication, non-contact with a sample, excellent de-coupling from surroundings, and high microwave power is directly coupled into the tissue.Â Parametric models for the dielectric spectrum of tissues. Physics in Medicine and Biology 41, 2271â€"2293.CrossRef Google Scholar PubMed. 34.Thompson, RH et al. Microwave thermoelastic imaging uses microwave-pulse-induced thermoelastic pressure waves to form planar or tomographic images.Â It discusses the science of thermoelastic wave generation and propagation in biological tissues; the design of prototype microwave thermoelastic tomographic imaging (MTTI) systems; and the reconstruction of tomographic images using filtered-back projection algorithms; as well as the performance of prototype microwave thermoelastic tomographic systems in phantom models and human subjects. Keywords. Dielectric Permittivity Biological Tissue Microwave Absorption Microwave Energy Microwave Pulse. These keywords were added by machine and not by the authors.