An Integrated Approach towards Functional Brain Imaging Using Simultaneous Focused Microwave Radiometry, Near-Infrared Spectroscopy and Electroencephalography Measurements

Panagiotis Farantatos, Irene Karanasiou*, and Nikolaos Uzunoglu

School of Electrical and Computer Engineering, National Technical University of Athens
9, Iroon Polytechniou, Zografou Campus, 15773, Athens, Greece
{pfaran,ikaran}@esd.ece.ntua.gr, nuzu@cc.ece.ntua.gr

Abstract. The scope of our ongoing research is the development of a multi-modal, multi-spectral methodology using non-ionizing radiation to study brain function. With this view, a novel microwave radiometry imaging and a near-infrared spectroscopy device have been integrated with an electroencephalogram (EEG) for concurrent measurements of blood flow, neural activity, temperature and conductivity changes in the brain. In this paper, a simulation study to identify whether the focusing properties of the microwave radiometry monitoring system are affected when used in conjunction with concurrent EEG and near-infrared spectroscopy measurements is presented. The simulations are performed using two head models and a phased array system as radiometric antenna receiver, which ensures scanning of the brain area of interest without the need of moving the subject or the monitoring configuration. The results of the electric field distributions inside the entire proposed imaging system illustrate the potential of integrating the three techniques into a single non-invasive monitoring intracranial system.

Keywords: functional imaging, microwave radiometry, functional near-infrared spectroscopy, electroencephalography.

1 Introduction

Functional neuroimaging is broadly defined as the imaging techniques that provide measures of brain activity [1]. These imaging modalities measure correlates of brain activity, and aim at linking the relationship between neural activity in certain brain areas to specific cognitive functions. The activation of specific brain regions is related to increased local neural activity and/or increased regional cerebral blood flow, blood volume, blood oxygen content, and changes in tissue metabolite concentration [2]. It is only in the past few decades that significant advancements have been made in both basic and clinical neuroscience towards the understanding of the subtle mechanisms

* Corresponding author.

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and complex relations of the structure and function of the human brain. This progress is of paramount importance, since the brain is not only the most essential organ in the human body because it ensures the vitality, quality and functionality of the rest of the body, but also because it is the organ of the mind and consciousness, the locus of our sense of selfhood and human existence.

In view of the recent advances in functional neuroimaging, current and future trends focus on synchronous combination of imaging modalities by integrating more than one measures of brain function, e.g., hemodynamic and electrophysiological (EEG and fMRI). These multi-modal approaches aim at achieving sufficient temporal and spatial resolution in order to localize neural activity by providing different expressions of the same phenomenon and identify the functional connectivity between different brain regions, assuming that the multi-modal information represents the same neural networks [3].

In this context, the scope of this research is to provide non-invasive, non-ionizing functional imaging comprising combined blood flow and neural dynamics information, as well as passive measurement of temperature and conductivity fluctuations during activation of specified brain areas in-vivo. The simultaneous acquisition of both hemodynamic and electrophysiological measures is critical for a better understanding of this neurovascular coupling. Moreover, different techniques measure different correlates of neural activity and are characterized by different attributes, e.g. spatial and temporal resolution. In addition, acquiring at the same time measurements of brain temperature and conductivity variations which have been associated with brain activation [4] provides additional insights to the understanding of the underlying mechanisms of brain function. Efforts are being made to achieve the aforementioned aims using a novel Microwave Radiometry Imaging System (MiRaIS) [5]-[7] integrated with a near-infrared spectroscopy system [8] and an electroencephalograph.

It should be noted that, the MiRaIS being a novel technique and non-standardized brain imaging technique, has been used for the past 6 years in various experiments in order to evaluate its potential as an intracranial imaging device [5]-[7]. One of the most important advantages of this method is that it operates in an entirely passive and non-invasive manner. It is able to provide real-time temperature and/or conductivity variation measurements in water phantoms and animals and potentially in subcutaneous biological tissues. Importantly, the system has been used in human experiments in order to explore the possibility of passively measuring brain activation changes that are possibly attributed to local conductivity and/or temperature changes. The results indicate the potential value of using focused microwave radiometry to identify brain activations possibly involved or affected in operations induced by particular psychophysiological tasks [5]. Following this rationale, if such changes can be measured with the proposed method, then it could be used to image brain activity in an entirely passive and non-invasive manner that it is completely harmless and can be repeated as often as necessary without any risk even for sensitive populations.

The work presented herein focuses on certain aspects of the incorporation of the various brain monitoring modules to a single modality and mainly on the effect of concurrent EEG and near-infrared measurements on the focusing properties of the

MiRaIS system. The simulations that were carried out in order to calculate the electric field distributions inside the entire proposed imaging system are performed using two head models, a spherical and a more anatomically detailed one. The radiometric antenna receiver is a phased array system, which ensures scanning of the brain area of interest without the need of moving the subject or the monitoring configuration. In the following sections, the details and the results of the simulation study are fully described and finally discussed in the relevant sections, investigating the potential of integrating three non-invasive brain monitoring techniques in a single system.

2 Materials and Methods

Based on the aforementioned, the systems and methodologies that are in the process of being implemented in one modality to achieve synchronous measurements of neural correlates and blood flow in conjunction with temperature and conductivity variation information, are presented in this section.

2.1 System Description

The operating principle of the Microwave Radiometry Imaging System (MiRaIS) is based on the use of an ellipsoidal conductive wall cavity to achieve beamforming and focusing on the brain areas of interest. The ellipsoidal beamformer is axis-symmetric with an opening aperture to host the human head that is monitored. The cavity has 1.25m length of large axis and 1.20m length of small axis (Fig. 1).

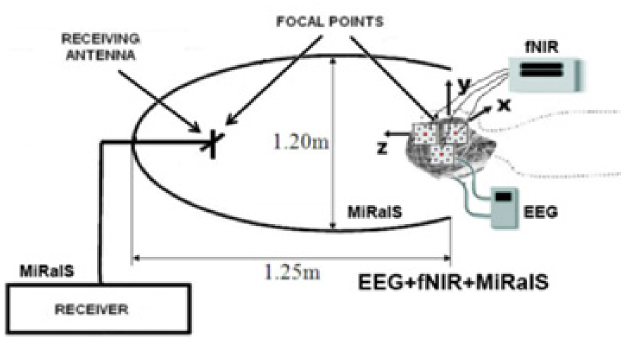


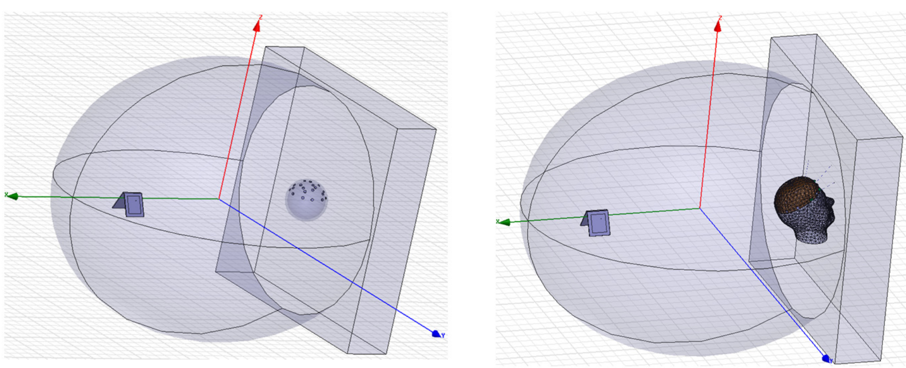
Fig. 1. Block diagram of integrated MiRaIS, Near-Infrared and EEG system

The geometrical properties of the ellipse indicate that rays originating from one focal point will merge on the other focal point. Exploiting this characteristic, when the system is used for microwave radiometry the medium of interest is placed at one focal point, whereas a receiving antenna is placed at the other one. In this way, the chaotic electromagnetic energy emitted by the medium of interest is received by the antenna and driven to a multiband radiometer (operating at 1-4GHz) for detection (Fig. 1). The receiving antenna used in this case is a phased array setup comprising patch antennas operating at 1.53GHz to achieve scanning of the areas under measurement. In the simulations presented herein the reciprocal problem is solved in order to reduce the computational cost imposed by the solution of the initial “forward” problem.

The MiRaIS is intended to be combined with a newly-developed CW pulsed fNIR system operating in the range of 650-850 nm that is compatible with both MiRaIS and EEG [8]. Finally, the electroencephalograph that will be used is a commercial system. All fNIR source and detector components as well as the EEG electrodes will be soon integrated and mounted on a customized head cap, according to the 10-20 system. This will allow concurrent EEG/fNIR and MiRaIS recordings. Therefore, the resulting multi-modal measurements will comprise electrical activity (EEG), blood flow and volume (fNIR), as well as temperature and conductivity variations (MiRaIS) in activated areas. The setup of the entire system is depicted in Fig. 1. The subject enters the ellipsoidal cavity wearing a headcap on which the EEG electrodes and the optical fibres of the near-infrared system are mounted (Fig. 3). The area to be scanned is placed on one focal area of the reflector while the microwave receiving antenna of the MiRaIS is placed on the other focus.

2.2 Simulation Setups

The analysis of the electromagnetic problem is approached numerically using commercial FEM solver (High Frequency Structure Simulator, HFSS, Ansoft Corporation). The simulations have been performed using a two element microstrip patch emitting antenna operating at 1.53GHz placed at the ellipsoidal focus with each element forming an angle of 60° with the horizontal axis (Fig. 2). It has been used as a phased array system and the system’s focusing properties have been investigated for phase difference value Δφ=60° and Δφ=90°.



(a) (b)

Fig. 2. MiRaIS Configuration with a) spherical head model b) SAM model placed at the ellipsoid’s reflector focus while the phased two-element antenna is placed on the other focal area

The analysis is performed for two types of head models; a spherical head model and a more detailed anatomic one (SAM -Standard Anthropomorphic Mannequin) whose shape and dimension are specified in a CAD (computer aided design) file included with EN 50361-2001 and IEEE 1528-2003. Both models are single layered having dielectric permittivity and conductivity mean values for brain grey matter at 1.53GHz. Both head models are surrounded by a matching lossless dielectric material of εr= 6.15 and 1cm thickness which, as previously shown [9], significantly improves the system focusing properties minimizing the electromagnetic wave scattering due to the more stepped change of the refraction index on the head–air interface.

The EEG electrodes and the optic fibers and photodiode detectors of the fNIR system have been placed on the head models. The EEG system comprises 16 electrodes modeled by aluminum cylinders of 11mm diameter and 3mm height. Three optic fibers for each one of the operating wavelengths of the fNIR system are placed on the frontocentral electrodes (FP1, FP2, Fz) and the three detectors in between having a distance of 5cm from each corresponding optic fiber. The diameters of the latter are 0.5mm and are modeled as glass fibers while the detectors are indium cylinders of 10mm diameter and height. The EEG and fNIR sensors have been integrated on a dielectric head cap and are depicted in Fig. 3.

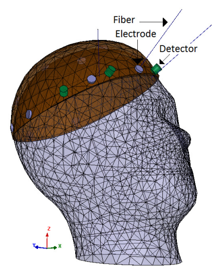


Fig. 3. Dielectric headcap with EEG electrodes and fNIR sources and detectors on SAM model

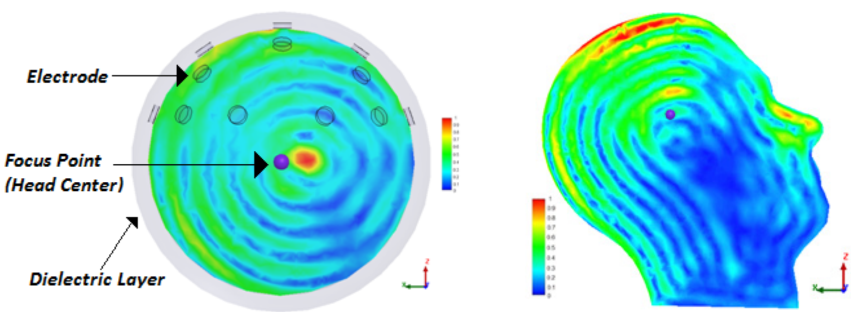
3 Results

In order to use a diagnostic device such as the proposed one, it is of great importance to have the ability to image any arbitrary area inside the human head, placed on the ellipsoid's focal point where the maximum peak of radiation is achieved. The main drawback that may occur when using the MiRaIs and the EEG, fNIR at the same time is the shielding mesh that may be created by the metallic parts of the EEG electrodes and fNIR system placed on the surface of the human head.

Therefore, the electromagnetic field inside the cavity volume and especially inside the spherical head model with the presence of the EEG electrodes has been calculated. As it is observed in Fig. 3a, sixteen electrodes (eight approximately at each hemisphere) maybe used at the frequency of 1.53GHz (and at all higher operation frequencies up to 4GHz) without raising any electromagnetic compatibility issues; the EEG electrode metallic parts do not affect the systems focusing properties and the electric field converges at the centre of the human head model when it is placed at the ellipsoidal focus. It should be noted as well that the electrode wiring should be cross-polarized to the MiRaIS receiving antenna in order to minimize any additional electromagnetic compatibility issues.

The fNIR system is not expected to particularly interfere with the MiRaIS operation since the three glass optical fibers have low dielectric property values and the only partially metallic parts (detectors) are placed on the frontocentral electrodes. In Fig. 3b, all system components have been mounted on the SAM head model with the latter's center placed on the ellipsoid's focus point. The electric field distribution inside the head model is depicted in the same figure and the simulation results fully verify theoretical expectations.

In all simulation cases with the integration of the three brain monitoring modalities, clear focusing inside the head models is achieved. Additionally, because of the two-element phased antenna, the focusing area inside the head model moves, performing a linear scan of 20 mm, approximately starting at a distance of varying from 5mm to 10mm away from the ellipsoidal focal point. The phase difference of the two microstrip antennas significantly affects the way the scanning inside the head model is achieved and thus with the appropriate selection of phase difference the scanning area may be successfully manipulated. This way scanning of the area of interest can be performed without moving the subject.



(a) (b)

Fig. 4. Electric field distribution in a) the spherical head model and b) SAM model when concurrent EEG, fNIR and MiRaIS measurements are performed

4 Discussion and Conclusion

Ongoing research during the past few years, envisions the development of an integrated functional imaging methodology to study brain function in-vivo through a multi-modal, multi-spectral approach using non-ionizing radiation to provide combined brain functional information. The proposed system comprises a microwave radiometry imaging module that provides the measurements of the local temperature and conductivity tissue variations, a near-infrared spectroscopy and EEG system that provide the blood flow and neural activity information respectively.

The present paper focuses on certain aspects of the incorporation of the various brain monitoring modules to a single modality and mainly on the effect of concurrent EEG and near-infrared measurements on the focusing properties of the MiRaIS system. Simulations were carried out to calculate the electric field distributions inside the entire proposed imaging system using two head models, a spherical and a more anatomically detailed one. The radiometric antenna receiver is a phased array system, which ensures scanning of the brain area of interest without the need of moving the subject to acquire tomographic data. The results show that the modules can be successfully integrated in a single imaging modality without any compatibility issues. Nevertheless, extensive experimentation of the whole system especially including human volunteers is essential in order to validate it as a potentially useful imaging tool in practice.

More precise assessment of the underlying biophysics of the measured signals will be extremely important for the better understanding of the healthy and diseased brain. The ultimate goal of the proposed methodology is to make joint inferences about the neural activity, hemodynamics, and other biophysical parameters of activated brain areas and the correlations between them, by exploiting complementary information from multimodal and multispectral information, through implementation of non-invasive and non-ionizing imaging techniques. The proposed unprecedented concurrent assessment of multiple biophysical correlates of neural activation (blood flow, volume and oxygenation, conductivity and temperature) will allow detailed correlation studies that will potentially further elucidate the nature of brain activation measurement and the neurovascular coupling.

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