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An Innovative Approach to Diffuse Optical Tomography Using Code Division Multiplexing

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Abstract

This paper introduces a novel approach to perform Diffuse Optical Tomography overcoming the limitation and high costs of Time Domain conventional methods, using a multichannel double stage coding technique. A preliminary numerical validation of the model is presented.

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Keywords: biophonics; CDMA; Diffuse Optical Tomography (DOT)

1. Introduction

Diffuse Optical Tomography (DOT) is an emerging medical imaging technique in which biological tissue is illuminated by arrays of light source in the near-infrared band, the multiply-scattered and/or absorbed light which emerges from the tissue is observed with detectors, then a physical propagation model is used to infer the localized optical properties of the illuminated tissue, in order to reconstruct one or more spatially variable optical coefficients. Nowadays, DOT is especially used to detect tumors in the breast and to image the brain (functional imaging). New targeted applications are for cardiac vital parameters monitoring in open chest surgery and trans-toracic investigation as well. This technique has seen a huge upsurge in the last years, but still presents a number of questioning in the technology and signal processing approach.

The propagation of near infrared photons in biological media has a diffusive nature, as photons are absorbed and massively scattered by tissues. In particular, the three primary absorbers at near-infrared wavelengths, water and both oxygenated and de-oxygenated hemoglobin, all have relatively weak absorption. This provides a spectral window through which we can attempt to localize absorption (primarily by the two forms of hemoglobin) and scattering in the tissue.

Time-resolved (TR) and Time-Domain Diffuse Optical Tomography (TD-DOT) techniques allow for concurrent estimation of both absorption and scattering coefficients extracted from the Temporal Point Spread Functions (TPSF), which is the temporal distribution of the arrival time of photons to the detectors. Most of TD-DOT techniques use ultrashort light pulses for tissue illumination and Time Correlated Single Photon Counters (TC-SPC) for detection. Although these systems offer high dynamic range, sensitivity and linearity, they are bulky, present a high cost and

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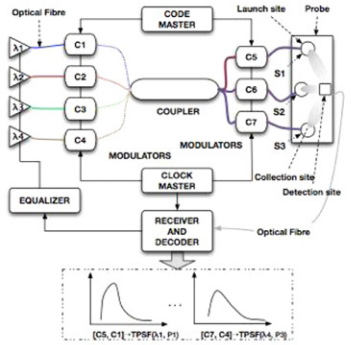

Figure 1. WS-CDM core module.

require absolute darkness during the long acquisition. A spread spectrum approach based on continuous wave (CW) source modulation by a pseudo-random bit sequence (PRBS) or more complex coding families allows overcoming these limitations by combining the advantages of time-resolved systems with those of low cost of components, lower sensitivity to ambient light, shorter acquisition time. Nevertheless only one wavelength and one emitting location at a time can be switched on, thus making the full acquisition from an array of sources and detectors a time consuming serial process.

The proposed work introduces a novel multichannel approach, based on the use of wavelength and code division multiplexing, applicable to diffuse optical imaging tomography; the approach, called WS-CDM (Wavelength and Space Code Division Multiplexing), essentially consists of a double stage intensity modulation of multi-wavelength CW laser sources using orthogonal codes (well known in radiocommunication CDMA systems) and a correlation-based decoding after propagation in the tissue, parallel acquisition of several wavelengths and from several locations is achievable; it promises better signal to noise ratio (SNR), higher acquisition speed, robustness to ambient light and lower costs compared to both the conventional systems.

This approach is also investigated in optical coherent tomography (OCT), which are promising candidates for the development of new high resolution and high performances tomographic techniques, allowing the imaging of subcellular structural and functional states of a tissue.

Figure 1 contains the functional description of the encoder in the configuration with four wavelengths (λ_1–λ_4), three launch sites ($S1$–$S3$) and one detector. Each light source is a double-encoded cheap CW distributed feedback (DFB) laser diode: the first set of words ($C1$–$C4$) encodes the wavelength, the second ($C5$–$C7$) the emission position. The emission power is dynamically and continuously equalized (this is a general requirement of telecommunication CDM system). All the diodes are always on (no scanning is necessary). The detector (the square in the figure) can be either an avalanche photodiode (APD) or a SPC, and reconstructs the global signal, containing all the wavelengths, from all the sources, at all their multiple paths. The correlation receiver operates a double decoding to reconstruct the single TPSFs: for instance, contribution from source $S1$ at λ_1 is obtained by cascade correlating the received signal with $C5$ and then $C1$. If $C1$–$C7$ are orthogonal and have Dirac-like autocorrelation, the simultaneous detection of delayed replicas of each channel is possible and TPSFs are extracted. A Matlab-based simulator is conceived to compare the performances of different coding families (PRBS, Gold, Kasami, Walsh) with reference to the level of multipath, the variance of the photon propagation time, the spectrum spreading factor, the length of the codes. In this work, we focused on the architecture of the core element and the encoder; results of simulations and preliminary laboratory experimental activity aimed at validating the technology are discussed. The promising results obtained so far [1,2] and the many potential improvements to DOT and OCT motivate the continuation of research on WS-CDM. It is indeed important to mention that improvements on the technology of optical active components are necessary: it is still difficult to find on the market fast electro-optical modulators with large bandwidth in the 690–900 nm range. Therefore, experimental activity has been carried on up to now in the telecom 1550 nm band, far from the near infrared range of interest for medical use (690–900 nm). This is not a limitation given the scope of the paper, but improvements on the technological side are mandatory (and are in the way of getting reached) for this technology to be fully implementable.

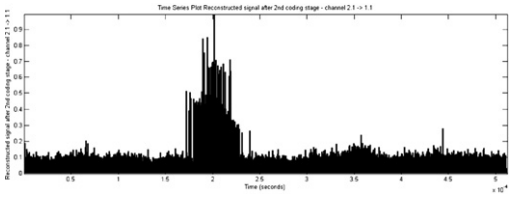

Figure 2. An example of ToF. The simulation has been performed using two 512-PRBS codes.

2. Preliminary results

Preliminary results of TD applied to cardiac tissue monitoring are presented in [3]. Firstly, we focused on numerical validation of the encoding/decoding technique. A Matlab-based simulator was developed to study the effects of different coding words families and length, spectrum spreading factor on the performances of the whole system in terms of SNR, speed of acquisition and reconstruction, robustness to non perfect channel equalization, depending on various diffusive and absorbing characteristics of the tissue.

It has been implemented a simple model of diffusion, in which photon delays are extracted from a gaussian distribution (as one can expect using a probabilistic approach to solve the diffusion equation). Then, the signals are subjected to a variable attenuation (to model the absorption) according to the conventional Lambert–Beer law. Figure 2 shows the ToF relative to signals passing through the first branch of each coding stage (see Figure 1).

3. Ongoing activities

More complex coding families are being considered and a more advanced detection architecture is being be implemented in order to minimize the interference component and improve the signal-to-noise ratio. The use of WS-CDM could be investigated in coherent optical methods, in order to expand the advantages introduced by the proposal approach to OCT. This research activity avails itself of the collaboration of the IFC (Clinical Physiology Institute, Pisa) and the POLDVII (Polytechnic Institute, Milano).

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