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The Design and Characterization of a Digital Optical Breast Cancer Imaging System

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Abstract—**Optical imaging has the potential to play a major role in breast cancer screening and diagnosis due to its ability to image cancer characteristics such as angiogenesis and hypoxia. A promising approach to evaluate and quantify these characteristics is to perform dynamic imaging studies in which one monitors the hemodynamic response to an external stimulus, such as a valsalva maneuver. It has been shown that the response to such stimuli shows MARKED differences between cancerous and healthy tissues. The fast imaging rates and large dynamic range of digital devices makes them ideal for this type of imaging studies. Here we present a digital optical tomography system designed specifically for dynamic breast imaging. The instrument uses laser diodes at 4 different near-infrared wavelengths with 32 sources and 128 silicon photodiode detectors.**

I.INTRODUCTION

Optical Tomography (OT) is a novel medical imaging modality that involves the delivery of near-infrared (NIR) light into tissue and measuring the transmitted and reflected light intensities at multiple positions along the surface [1,2]. Using multiple wavelengths one can reconstruct the data and gain insight into the distribution of chromophores such as oxy- and deoxy-hemoglobin, lipid concentration and water [3,4]. Using information about the chromophore distributions, OT can detect changes in metabolic activity and vascularization related to growing tumors [3,5]. As a result, OT has the potential to impact the early detection and diagnosis of breast cancer.

In recent years there have been a number of clinical studies published from research groups around the world that use optical tomography for the detection of breast tumors. For example, Rinneberg et al and Grosenick et al, both with the Physikalische- Technische Bundesanstalt, have published clinical results using a dual wavelength time-domain optical mammography system [6,7]. Culver et al have developed a combined frequency domain and continuous-wave clinical system that uses six wavelengths [8], and Enfield et al published results from a three-dimensional time-resolved optical mammography study [9]. Most recently, Boverman et al presented a diffuse-optical-tomography study that explored hemoglobin levels in the breast [10].

Many of the existing optical tomography systems utilize analog technology. Generally, compared to digital systems, analog systems have more noise due to external noise sources such as power supplies, coupling from other channels, and electronic non-linearities [3]. To reduce these effects, lock-in detection algorithms are typically employed, which can separate the system response from the background noise by modulating the illumination sources and synchronously demodulating the detected signal [3,11]. It has been shown that lock-in detection algorithms that are implemented using digital devices are faster and have less electronic nonlinearities, less signal drift, and less gain errors than analog lock-in detection implementations [12]. In addition, digital systems have excellent scalability as well as improved temporal resolution and measurement accuracy.

This paper discusses the design of a dynamic breast imaging device that makes use of the benefits of digital electronics. One of the advantages of this design is that it uses a large number of sources and detectors while still attaining fast imaging rates. Some of the challenges of this design include the timing of the light delivery and acquisition, the streamlined processing of such a large number of source and detector points, and the creation of a user interface that can seamlessly transition into the clinic. We have achieved considerably better dynamic range and can acquire data at higher speeds and with better precision than comparable analog electronics-based systems.

II.SYSTEM DESIGN

A.System Overview

The system involves three main components: a light delivery unit, a control unit, and a detection unit. The input unit contains 4 laser diodes that deliver NIR light at 4 wavelengths to a switch that moves the light between 32 different sources. These sources simultaneously illuminate both the left and right breasts. The sources and detectors are brought into contact with the breast using a newly designed adaptive dual breast measuring head. Each measuring head uses eight, precision linear translating articulating arms that have a pivoting fiber-optic support that can contour to various breast geometries.

The measuring head also brings 64 detectors into contact with each breast for a total of 128 detectors. As shown in Table I, with 32 sources, 128 detectors, and 4 wavelengths

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there are 16 384 total data points per image frame. The light that is transmitted and reflected through the tissue is captured by the detector fibers and is sensed using silicon photodiodes. The photodiodes convert the light into a current which is amplified, converted to a voltage, and then quantized using an analog-to-digital converter (ADC) chip. From there the signal is passed onto the digital signal processor (DSP) which demodulates the data and passes the result onto the personal computer (PC) via a National Instruments Peripheral Connection Interface Data Acquisition Card (DAQ). A flowchart of the system is shown in Fig. 1.

TABLE I
SYSTEM PARAMETERS

Parameter	Value
Sources	32
Detectors	128
Wavelengths	4
Total Data Points per Frame	16 384

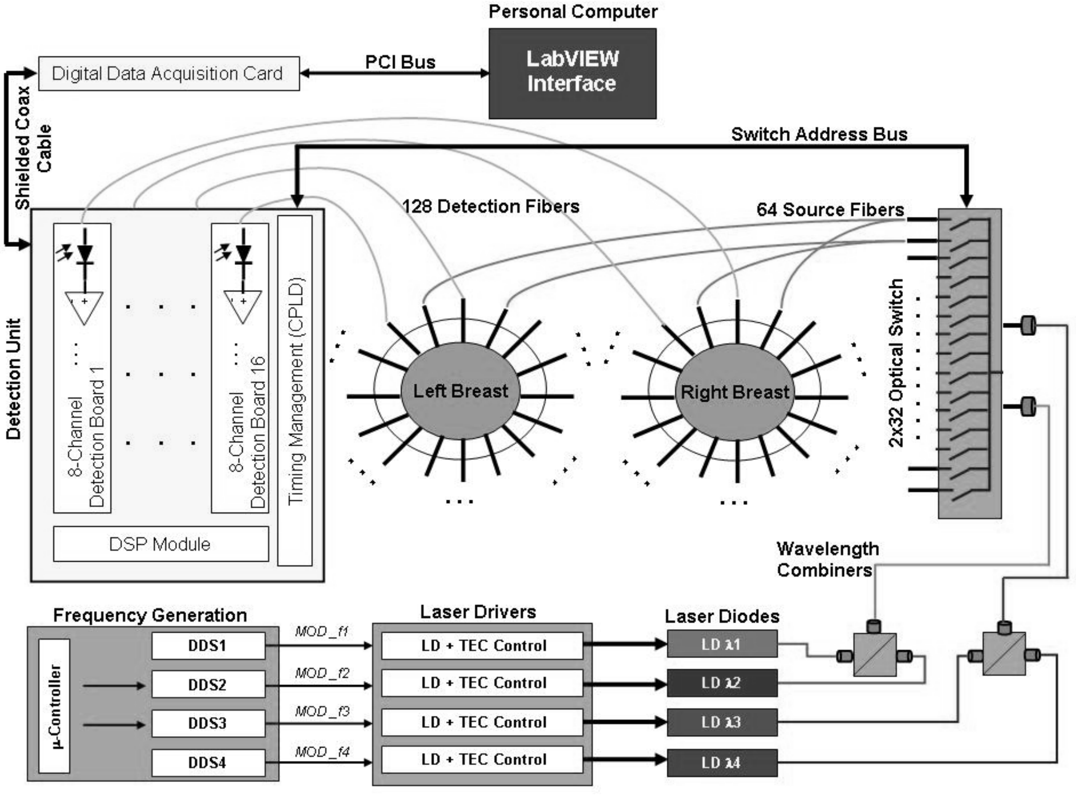

Fig. 1. Flowchart of the system layout and signal communication for the digital breast imaging system.

The control unit of the device handles the timing of the input and detection units using a complex programmable logic device (CPLD). The control unit also facilitates the control over the laser input unit and the detection unit through a LabVIEW user interface running on the PC. Through this interface the user can control the gain settings, the imaging start and stop times, as well as the number of sources and detectors to use for the experiment.

B. Multi-wavelength Illumination

In order to be able to spectroscopically determine the concentrations of various chromophores such as oxyhemoglobin, deoxyhemoglobin, and water, our system utilizes measurements from 4 wavelengths. By modulating the laser diodes at different frequencies and then combining the outputs, we can perform simultaneous multi-wavelength measurements.

Due to the fact that the system is measuring small optical signals which result from attenuation by the spatially heterogeneous optical absorption and scattering properties of tissue, noise corruption is a serious issue. Modulating the laser light reduces the noise because it allows for the use of digital lock-in detection which is a bandwidth narrowing technique that is immune to background DC noise. In order to modulate the input light the device uses direct digital synthesis (DDS) to generate a stable and accurate modulation frequency to feed into the laser driver. The frequency is controlled by a programmable microcontroller located on the backplane of the input unit. The system combines two wavelengths of light into each input fiber using 2x1 optical combiners. Two fibers containing a total of four wavelengths feed into an optical switch that switches the light between 32 output fibers that deliver the light to the tissue. The Sercalo® switch that is used in our system can switch between output positions in less than 5 milliseconds.

C.Digital Detection and Gain Settings

The system uses silicon photodiodes to detect the transmitted and reflected light at the tissue surface. Silicon photodiodes are suitable for this application due to their sensitivity, frequency response, and linearity. Due to the fact that the detection fibers are arranged surrounding the tissue, some fibers receive large amounts of light power, while other fibers receive almost no light power. In order to overcome this discrepancy, there are two analog voltage amplification stages placed directly following the photodiode. The first stage is a trans-impedance amplifier (TIA) that has a range of amplification from 10kV/A to 100 MV/A. The TIA amplification stage then feeds into a programmable gain amplifier (PGA) that has a range of amplification from 1 to 1000 V/V. This gives an overall voltage gain of $20\log(10^7) = 140$ dB. In addition, since the ADC uses 16 bits of precision it contributes $20\log(2^{16}) = 96$ dB. This gives a total dynamic range of 236 dB. The gain of the voltage amplification stage is controllable through the LabVIEW user interface and the interface also includes routines to automatically determine the optimal gain settings for each channel. The ADC is capable of 0.0015% full-scale resolution, which gives a theoretical ability to detect 0.0075% fluctuations for signals as small as 10pA.

D.DSP and System Timing

The digital signal processing (DSP) portion of the system is responsible for coordinating the data acquisition, processing, and transfer. It is composed of a 32-bit floating point DSP chip, an Analog Devices Inc. ADSP-21161N, complemented by supporting circuitry. The processor is a single-instruction-multiple-data (SIMD) structure that can operate at 100 MHz which means that it can carry out 600 million math operations per second. Furthermore, up to 1 megabit of data and code can be stored in the on-chip SRAM.

The DSP's main role is to extract the amplitude of the modulated signal which is buried in a noisy background using digital lock-in detection. Using a set of reference signals generated at the modulation frequencies set by the input unit, the system is able to distinguish each wavelength from the others and from the noisy background. The DSP mixes the input with cosine and sinusoidal reference signals for each wavelength's frequency. The frequently termed "in-phase" and "quadrature channels" are then low-passed filtered. The amplitude is then calculated using the Pythagorean Theorem [13].

By carefully parameterizing the sampling frequency, the modulation frequencies and the number of samples collected, one can utilize an averaging filter and its superb white noise immunity, while at the same time completely eliminating any distortion from unwanted frequencies that are previously generated by mixing. Equation (1) shows the optimal relationship between sampling frequency, modulation frequency, and sample size where F_m is the modulation frequency, F_s is the sampling frequency, N_s is the number of samples acquired and k is any positive integer.

$$F_m = k\frac{F_s}{N_s} \qquad (1)$$

When the parameters are chosen to satisfy this relationship, the frequency of interest can be uniquely extracted while others are zeroed out [13].

The timing management of the system is handled using a complex programmable logic device (CPLD). The CPLD is an Atmel ATF1508 chip with 128 macro-cells, 96 bidirectional I/O pins, and runs on a 30 MHz clock. One of the CPLD's main tasks is to coordinate the timing of the input and output units. The CPLD tells the switch when to move to a new optical source position, and then waits for the appropriate amount of time (5ms for the Sercalo® switch used in this system) to account for the mechanical switching before instructing the DSP to acquire and process the detected signal. As part of that switching procedure the CPLD must also coordinate updating the gain bits to each of the detector channels. For each source position it takes 5 ms to adjust the optical switch, during which time the gain settings are updated, and then another 2 ms for the ADC to sample 150 samples at 75 kHz, which means that it takes a total of 7 ms for each source position. Overall, with 32 source positions, it takes 0.44 s to acquire a full frame of data, which makes the frame rate for our system 2.27 frames per second.

In order to handle the data from 128 detector channels, 32 sources, and 4 wavelengths we use two DSP chips and two CPLD chips arranged in a master and slave configuration. The master chips are responsible for the control signals and the slave chips are only responsible for data processing. The master chips control the operation of the slave chips. This configuration keeps all of the chips synchronized while maximizing the throughput of the data.

E.User Control

The user control portion of the device is an essential portion as it gives the user the ability to configure the system, adjust the gain bits, as well as process and display the acquired data. The user interface is also able to automatically detect the optimal gain settings for each source and detector pair.

The host PC uses a National Instruments LabVIEW program for its interface which interacts with the DSP and hardware components of the system through a PCI Data Acquisition Card (DAQ). The DAQ card is not only responsible for handling the control lines between the DSP and the user interface, but it is also responsible for streamlining the data.

III.DISCUSSION

We have given an overall description of our new digital dynamic optical tomographic breast imaging system. In particular, the design considerations and rational for the input, detection, and timing detection modules were discussed. Signal conditioning and digital lock-in were explained.

Table II illustrates some of the performance differences between the new digital breast imager and previous generations of optical tomography systems [11,12].

The system has a theoretical dynamic range of 236 dB and a frame rate of 2.27 frames per second. The high dynamic range will improve our signal to noise ratio and will result in higher sensitivity than other OT devices. The simultaneous illumination of both breasts and the large number of detectors means that we can acquire images from both breasts at the same time. The high frame rate means that we can acquire four times the amount of data than other systems in the same amount of time. Overall, these characteristics make this system well suited for dynamic breast imaging, where the response to an external stimulus, such as pressure change or the valsalva maneuver, are recorded.

TABLE II
COMPARISON BETWEEN FIRST GENERATION ANALOG IMAGER (DYNOT), FIRST GENERATION DIGITAL IMAGER AND THE BREAST DIGITAL IMAGER.

	DYNOT	First Generation Digital Imager	Breast Digital Imager
Mode of Operation	CW	CW	CW
No. of Wavelengths	1-4	1-2	1-4
No. of Sources	25	16	32
No. of Detectors	32	32	128
Data Points	3200	1024	16 384
Acquisition Time	0.37 s	0.11 s	0.44 s
Frame Rate	2.7 Frames/s	9.09 Frames/s	2.27 Frames/s
Data Rate	8640 Points/s	9216 Points/s	32 864 Points/s

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