Design of a Digital Optical Tomography System for Dynamic Breast Imaging

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Abstract: We present the design of an optical breast imaging system, which is, unlike currently available analog instrumentation, based on digital conversion, processing, and filtering techniques. The system consists of 128 silicon photodiode detectors, 64 excitation points, and 4 near-infrared laser diodes. We provide detailed insight into signal conditioning, timing and light delivery to achieve robust and dynamic imaging.

1. Introduction

Over the past decade, optical tomography (OT) has been developed for laboratory research and clinical application.[1-9] This novel medical imaging modality is based on delivering low energy and near-infrared (NIR) electromagnetic radiation ranging from 700nm to 900nm onto the surface of the object under investigation. By detecting transmitted and back-reflected intensity at multiple positions along the surface, we can reconstruct tomographic images of the tissue's structure, optical properties and physiologic processes. With multi-wavelength reconstruction, one can derive the distribution of physiologically-relevant chromophores such as oxy- and deoxy-hemoglobin, lipid concentration and water content. [1,4,5,9]

Today, most optical tomography systems execute imaging signal operation in the analog domain. Such analog systems are prone to external noise (power supply lines and ambient light) and internal noise (photon-detection, resistive elements, amplifiers, etc.).[1] To reduce these artifacts, some researchers use lock-in detection schemes to separate system response from the noisy background by modulating light sources and synchronously demodulating the detected signal.[1,6] However, since these systems are implemented with analog devices, their performance is limited by slow response, electronic nonlinearity, signal drift, gain errors, etc. Our group has recently shown that superior performance can be achieved by switching from analog to digital-electronics-based systems.[9] In this paper we adapt this digital technology to the specific application of dynamic breast imaging. There are unique challenges related to this approach such as system expansion, timing consideration, acquisition speed, and clinically practical user interface design. In the following we describe in detail the various design considerations and practical implementation. We have achieved considerable better SNR values and can acquire data at higher speed and precision than comparable analog-electronics-based systems.

2. Methods

2.1 Instrument Layout

The imaging system is schematically shown in Figure 1. The system can image two breasts using 64 sources and 128 detectors at the same time. There are 4 laser diodes with different NIR wavelengths being modulated at their output intensity. Light beams are combined before the optical switch, which sequentially sends the beam to the source fiber bundles. Using a newly designed adaptive dual breast measuring head, 32 fibers are brought into contact with each breast. . Each breast unit has eight, precision linear translating articulating arms that have an attached pivoting fiber-optic support member that can contour to various breast geometries. The unit is fully motorized and can be addressed through computer control.

The dual breast-imaging head also brings 64 detector fibers in contact with each breast. The light transmitted through the tissue and captured by these fibers is sensed by individual SiO_2-photodetectors and converted into an electrical voltage. After an adaptive amplification stage, analog-digital-conversion (ADC) chips sample the continuous signal and pass it to the digital signal processor (DSP), which is at the core of the breast imager. The DSP demodulates the data and gets the DC result which is then sent to the personal computer (PC) through National Instruments Peripheral Connection Interface (PCI) data acquisition (DAQ) cards for reconstruction.

Users are able to control the laser output and detection performance through a LabVIEW interface running on the PC. The parallel data acquisition architecture allows us to achieve high temporal resolution for real-time, dynamic and multi-channel imaging.

2.2 Multiwavelength Illumination

CW instruments measure the change in optical intensity as a result of the spatial heterogeneity of attenuation and scattering properties of tissue. In practice, noise corruption is a serious issue in the final recovered image and thus it is important that a dedicated and robust noise reduction design be incorporated into the design of the light input module. A simple and effective method for reducing noise is modulating the laser intensity and demodulating the detected signal to extract the actual attenuation. On the other hand, considering our interest in imaging multiple physiologically-relevant chromophores, multi-color measurements must be carried out. To separate signals of different colors, it is required to encode the light sources with characteristics such as modulation frequency. In our case, we employ a technique known as direct digital synthesis (DDS) to generate stable and accurate modulation frequencies, which are tuned and controlled by a microcontroller through a parallel bus. The modulated laser outputs with different carrier frequencies are then coupled together, forming one beam for the optical switch to perform time-division multiplexing. Based on MEMS technology, the opto-mechanical switch houses 32 channels and is able to achieve a switching time less than 4 mini second.

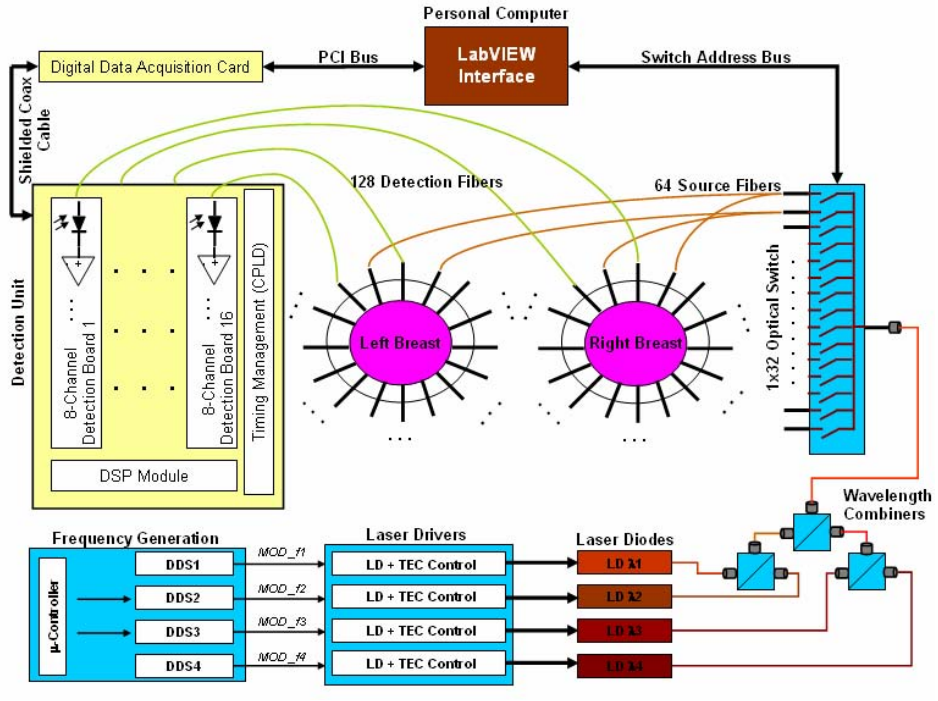

Figure 1: Flowchart of System Layout and Signal Communication

2.3 Signal Acquisition and Adaptive Gain Setting

The light emerging from the target tissue is sensed by silicone photodiodes, which provide sufficient sensitivity, frequency response, and linearity for our application. The arrangement of detection fibers determines that some channels receive very high light power while some others get almost nothing but dark current. To overcome this discrepancy, a voltage-amplification stage is placed immediately after the photodetectors. The gain of each voltage-amplification stage can be dynamically adjusted through the LabVIEW interface while the system is running. In our design, there is a combination of trans-impedance amplifiers (TIA) and programmable gain amplifiers (PGA) in the gain stage. With the support circuitry interfaced to the DSP, the TIA and PGA together offer a gain between 1 and 10^7 V/V, yielding a dynamic range of 140 dB and an absolute maximum imaging signal gain of 10^{10} (200 dB). The 16-bit ADC ($f_{sampling}$=75kHz) we utilize is capable of achieving 0.0015% full-scale resolution, thus our detection channels can theoretically detect 0.075% fluctuations for signals as small as 10pA.

2.4 DSP

In our system, the DSP plays a central role in collecting, processing, and filtering imaging data and finally routing the result to the host PC. Here we choose the high-performance 32-bit floating point DSP, ADSP-21161N, made by Analog Devices Inc. This chip is featured by the Super Harvard Architecture (SHARC) core. With the single-instruction-multiple-data (SIMD) structure operating at 100MHz, the processor can carry out 600 million math operations per second. Up to 1 megabit of data and code are stored in the on-chip, dual-ported SRAM. The direct-memory-access (DMA) frees the processor core from intervening block data transfer between memories and interfaces, which provides great flexibility when dealing with millions of bits of imaging data.

To extract the modulated signal buried in a noisy background, a bandwidth narrowing algorithm called lock-in detection is implemented in DSP. The reference signal is generated at the modulation frequency set by the DDS. When multiple carrier frequencies are used for different colors of light, they are superimposed together with corresponding references. As a result, the system is able to respond to a distinct color while discriminating others, in addition to the reduced noise level. The DSP internally produces in-phase and quadrature references for each modulated signal set, and then mixes them before routing them to a low pass filter. The final output is a DC signal immune to modulation frequency and phase difference, but only linearly conditioned to the optical power from the imaging target.

An averaging filter is used as the digital low pass filter to obtain the final DC signal. Through careful selection of the sampling frequency, modulation frequency and the sample size, the frequency of our interest can be uniquely extracted while others are zeroed out[9]. The relationship between these parameters is:

$$\mathrm{F_m} = \mathrm{k}\frac{F_s}{N_s}$$

Where $\mathrm{F_m}$ is the modulation frequency, $\mathrm{F_s}$ is the sampling frequency, $\mathrm{N_s}$ is the number of samples acquired and k is any positive integer. In fact, there exists a trade off between $\mathrm{F_s}$ and $\mathrm{N_s}$ [9] but we will not discuss the details here.

2.4 PC Control and System Timing

The operational control and data reconstruction of our breast imager is managed by a dedicated host PC, which uses a National Instruments LabVIEW program as its interface. The function of this program includes system configuration, gain bit programming, data display and post data processing. The LabVIEW program communicates with the DSP and other timing units through specific I/O tasks. Those tasks are realized by the PCI DAQ cards made by National Instruments. Another function of DAQ card is to streamline demodulated signal from the DSP to the host PC. The 32-bit parallel data lines are grouped into separate ports as either input or output, while handshaking protocols are employed to govern data transfer with 20MHz maximum internal sampling rate. Moreover, the adaptive gain selection is done by LabVIEW through scanning all possible gain values and choosing the optimal ones for corresponding source-detector pairs.

While the overall operation of the system is coordinated by the DSP, the timing management is controlled by a complex programmable logic device (CPLD). For instance, the optimal gain bits need to be updated for each detector channel after the source is switched; the ADCs must be paused for a sufficient amount of time to allow for the settling of the optical switch and analog electronics; the digitization of the signal must be time-division multiplexed so that the final signals can be efficiently routed to DSP. We choose ATF1508 as our state machine which has 128 macro-cells, 96 bidirectional I/O pins, and is driven by 30MHz clock.

3. Discussion

We have given an overall description of our new digital dynamic optical tomographic breast imaging system. The design considerations and rational were discussed and insight into the input, detection, and timing modules were offered. Signal conditioning and digital lock-in were explained. Currently, the system is undergoing additional testing before it will be deployed for clinical breast imaging studies.

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4. References

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