Rowan University

Rowan Digital Works

Theses and Dissertations

8-12-2009

Functional near-infrared spectroscopy for Hb and HbO₂ detection using remote sensing

Rane M. Pierson
Rowan University

Follow this and additional works at: <https://rdw.rowan.edu/etd>

Part of the [Electrical and Computer Engineering Commons](#)

Recommended Citation

Pierson, Rane M., "Functional near-infrared spectroscopy for Hb and HbO₂ detection using remote sensing" (2009). *Theses and Dissertations*. 657.
<https://rdw.rowan.edu/etd/657>

This Thesis is brought to you for free and open access by Rowan Digital Works. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of Rowan Digital Works. For more information, please contact graduateresearch@rowan.edu.

FUNCTIONAL NEAR-INFRARED SPECTROSCOPY FOR Hb AND HbO₂
DETECTION USING REMOTE SENSING

by
Rane M. Pierson

A Thesis

Submitted in partial fulfillment of the requirements of the
Master of Science in Engineering Degree
of
The Graduate School
at
Rowan University
August 12, 2009

Thesis Chair: Dr. Linda Head

© Rane M. Pierson 2009

ABSTRACT

Rane M. Pierson

FUNCTIONAL NEAR-INFRARED SPECTROSCOPY FOR Hb AND HbO₂ DETECTION USING REMOTE SENSING

2008/09

Dr. Linda Head

Master of Science in Engineering

The goal of the work presented in this thesis is to develop a wireless, near-infrared (NIR) imaging system to provide flexibility and functionality to clinicians and researchers who require monitoring of blood perfusion to tissue, muscles, or the brain. The prototype device uses a single stimulus/detection unit composed of an Epitex NIR LED with three wavelength options: 730, 805, and 850 nm, and an OPT101 photodiode detector. The device can be used to detect changes in the levels of oxygenated and deoxygenated hemoglobin in the body by measuring the amounts of absorbed and backscattered light at the wavelength associated with the correct compound. The backscattered light collected by the optical sensor is converted to a digital, serial bit stream for wireless transmission to a base station computer. The usefulness of this design may significantly change the way in which researchers and clinicians study the human body. Without the need to attach a subject to bulky equipment and confine them to a laboratory setting, the investigator can gather data unrestricted by the experimental setting. This advantage permits a vital metabolic indicator to be studied in many different and extremely difficult situations.

ACKNOWLEDGEMENTS

I would first like to thank Ryan Elwell and Terry Hopely for their preliminary work on the fNIRS imaging system and for laying the groundwork for which I have built upon. I also want to thank Andrew Flanyak, Jessica Donovan, and Michael McDonald for all of their hard work in the development of the fNIRS imaging system prototype, as well as Phil Mease and Daniel Brateris for their assistance over the course of this thesis. I would also like to thank my girlfriend and family for all the love and support that have shown me in everything that I have accomplished. It is because of them that I have accomplished such great things and I am forever grateful for their support.

I also want to thank the Rowan University engineering faculty for offering me an outstanding undergraduate and graduate education that has helped me to become a strong engineer with a great knowledge of the field. Specifically, I would like to thank Dr. Linda Head for providing me the opportunity work alongside her and for mentoring me throughout my graduate career. Without all of her help and support along the way, none of this would be possible. I would also like to thank the Department Chair Dr. Shreekanth Mandayam and the thesis committee members, Dr. Robert Krchnavek and Dr. Jennifer Kadlowec, for taking the time out of their busy schedules to be apart of this thesis.

TABLE OF CONTENTS

CHAPTER I	1
1.1 Overview of Medical Monitoring Techniques	1
1.1.1 Electroencephalography (EEG)	1
1.1.2 Magnetoencephalography (MEG)	2
1.2 Overview of Medical Imaging Techniques	3
1.2.1 Magnetic Resonance Imaging (MRI)	3
1.2.2 Positron Emission Tomography (PET)	4
1.2.3 X-Ray Tomography	4
1.3 Overview of Functional Near-Infrared Spectroscopy (fNIRS)	5
1.4 Scattering	8
1.4.1 Rayleigh Scattering	10
1.4.2 Debye Scattering	11
1.4.3 Mie Scattering	12
1.5 Three Types of fNIRS Imaging	13
1.6 Modified Beer-Lambert Law (MBLL)	13
CHAPTER II	16
2.1 Overview of the fNIRS Wireless Imaging System	16
CHAPTER III	17
3.1 Sensor Design Overview	17
3.2 Sensor Development	17
3.2.1 Sensor Mold	17
3.2.2 Sensor Fabrication	18
3.2.3 Power Management	19
CHAPTER IV	23
4.1 Wireless System Data Processing and Control Circuitry Overview	23
4.1.1 Variable Gain Amplifier (VGA)	24
4.1.2 8-bit Analog to Digital Converter (ADC)	25
4.1.3 4-Bit Counter	25
4.1.4 NAND Gate and Inverter	26

4.1.5 Flip-Flop	27
4.1.6 On-Board Clock	28
4.2 Circuit Schematic	28
4.3 Circuit Timing.....	29
4.4 Altium Designer™ and Board Fabrication	30
CHAPTER V	33
5.1 Wireless Communication Overview.....	33
5.2 Wireless Data Links	34
5.3 Configuring the Modules.....	35
5.4 MAX232 and Serial Communication	35
CHAPTER VI	37
6.1 Phantom Development Overview	37
6.2 Creating the Phantoms	38
6.3 System Characterization.....	39
6.3.1 Testing for Backscattered Light	39
6.3.2 Varying Levels of TiO ₂	41
6.3.3 Signal Detection Sensitivity to Different Absorber Concentrations	43
CHAPTER VII.....	44
7.1 Wireless Communication Software.....	44
7.1.1 Connect.m.....	44
7.1.2 Convert.m	45
7.1.3 Compare.m	47
7.2 Real-Time Data Plotting	48
CHAPTER VIII	50
REFERENCES	52
APPENDIX A – Epitex LED Spec Sheet.....	54
APPENDIX B – OPT101 Photodiode Spec Sheet.....	55
APPENDIX C – Variable Gain Amplifier Spec Sheet.....	57
APPENDIX D – Analog to Digital Converter Spec Sheet.....	58
APPENDIX E – Counter Spec Sheet	60
APPENDIX F – NAND Gate Spec Sheet.....	62

APPENDIX G – Inverter Spec Sheet.....	63
APPENDIX H – Flip-Flop Spec Sheet.....	65
APPENDIX I – On-Board Clock Spec Sheet.....	66
APPENDIX J – MATLAB™ Code	68
Connect.m.....	68
Convert.m	69
Compare.m.....	71
GUI.m.....	73

LIST OF FIGURES

Figure 1.1 - Absorption Spectrum in NIR Window [16]	6
Figure 1.2 - Graphical Representation of the Three Types of Photon Scattering	9
Figure 1.3 - Example of Rayleigh Scattering.....	11
Figure 1.4 - Example of Mie Scattering.....	12
Figure 1.5 - Example of Large Object Mie Scattering.....	13
Figure 3.1 - Optical Sensor Mold Developed in SolidWorks™.....	18
Figure 3.2 - Optical Sensor Mold	18
Figure 3.3 - Switching Circuit for the Different LED Wavelengths.....	20
Figure 3.4 - Internal Photodiode and LED Wiring	21
Figure 3.5 - The Optical Sensor.....	22
Figure 3.6 - Optical Sensing Array	22
Figure 4.1 - Wireless System Block Diagram	24
Figure 4.2 - Data Processing and Control Circuitry Schematic.....	29
Figure 4.3 - Timing Diagram.....	30
Figure 4.4 - Data Processing/Control Circuitry Board Altium Designer™ Schematic.....	31
Figure 4.5 - Altium Designer™ Printed Circuit Board Layout.....	31
Figure 4.6 - Top and Bottom View of the Manufactured PCB.....	32
Figure 5.1 - Radicom WHM900 Antenna [25].....	33
Figure 5.2 - Transmitting Wireless Module.....	34
Figure 6.1 - Plexiglas Phantom Mold	39
Figure 6.2 - Control Test Setup Configuration With A Clear Phantom	40
Figure 6.3 - Test Setup Configuration for Varying TiO ₂ Concentrations.....	41
Figure 7.1 - Connect.m Command Window Output.....	45
Figure 7.2 - Convert.m Command Window Output	46
Figure 7.3 - Voltages Saved to the Text File	46
Figure 7.4 - Voltage Plot with Ambient Light.....	47
Figure 7.5 - Compare.m Comparison Plot for 3 Different Test Runs.....	48
Figure 7.6 - Real-Time Voltage Plot.....	49

LIST OF TABLES

Table 3.1 - LED Operating Voltages for Each NIR Wavelength (See APPENDIX A) ...	19
Table 3.2 - Pin Configuration For Each LED Wavelength.....	21
Table 4.1 - Flip-Flop Outputs of the Counter	26
Table 4.2 - NAND Gate Outputs with Q0 and Q2 Inverted	27
Table 6.1 - The Four Main Elements of a Phantom.....	38
Table 6.2 - Data Collected at 805 nm	40
Table 6.3 - Voltage Readings for TiO ₂ Concentrationons on Black/White Surfaces	42
Table 6.4 - Voltage Response at 805 nm with Increasing Amounts of Carbon Black	43

CHAPTER I

INTRODUCTION

As technology and medical understanding of the human body continue to increase in complexity, the need for simpler, more efficient means of non-invasive medical imaging techniques must be established. Over the course of human history, the medical profession has searched for newer and more efficient medical tools and remedies to maintain a healthy society. Since early understanding of the atomic world, researchers have developed countless methods for diagnosing and treating illnesses through understanding the chemistry involved in creating pharmaceutical drugs and the physical laws that govern modern technology. This thesis describes the development of a hardware system that allows for an inexpensive, simple, and non-invasive method for studying the human body.

1.1 Overview of Medical Monitoring Techniques

Although the focus of this thesis is on medical imaging, it is important to first look at the medical monitoring techniques that are commonly used by clinicians and researchers. The two most common are the EEG and MEG which will be discussed in Section 1.1.1 and Section 1.1.2.

1.1.1 Electroencephalography (EEG)

The simplest way to monitor brain activity is by using electroencephalography (EEG). An EEG test is used to monitor electrical activity in the brain. By monitoring brain activity, it is possible to detect anomalies in brain function and the EEG offers a simple

way to perform this monitoring. During an EEG, many electrodes are placed in specific locations on the scalp to detect and observe different electrical patterns within the brain [1]. This is achieved by recording sets of electrical potential differences between pairs of electrodes [2]. However, there is currently no mathematical model of EEG activity, so researchers have been implementing different methods of analyzing the stochastic and deterministic features found in these signals. EEG is a good method of brain monitoring for detecting diseases like epilepsy due to the large potentials it generates between electrodes [3]. However, it is not nearly as helpful as imaging techniques are for detecting other types of diseases.

1.1.2 Magnetoencephalography (MEG)

An MEG is a technique that is used to measure the magnetic fields generated by the electrical activity of the brain's neurons. This technique provides information about the dynamics of induced and impulsive neural activity and the locations of their corresponding sources in the brain. Performing an MEG requires the clinician to place a superconducting quantum interference device, also known as a SQUID, on the patient. The SQUID detects magnetic fields with low noise interference and converts the magnetic flux into voltages, which allows detection of weak neuro-magnetic signals. A typical MEG device has approximately 300 SQUID devices within an array contained in a helmet that the patient wears, called a dewar. This allows for simultaneous measurements at different locations of the brain [4]. MEG signals result from current flowing throughout the cortex. These brain currents can be measured accurately with EEG whereas MEG does not require the sensors to physically contact the head. Therefore MEG is easier, faster, and less invasive to implement than EEG [2]. In

general, EEG and MEG both provide good temporal resolution, but locating the origins of the electrical and magnetic signals is difficult. Also, the spatial resolution of EEG and MEG is inferior to imaging techniques such as fMRI [5].

1.2 Overview of Medical Imaging Techniques

Before describing the details of functional near-infrared spectroscopy (fNIRS), we first review other types of medical imaging currently in use today. The following sections 1.2.1-1.2.3 will give an overview of three of the most popular types of medical imaging: MRI, PET, and X-Ray.

1.2.1 Magnetic Resonance Imaging (MRI)

Magnetic resonance imaging (MRI) uses the phenomenon of nuclear magnetic resonance (NMR) to map the brain. Most of the physical and chemical properties associated with objects leave a faint mark on the NMR signal that is detectable. This has made the MRI flexible for imaging the body and the brain. An MRI can detect the locations of neuronal processing in the brain associated with different tasks. These tasks, whether mental or physical, are detected by identifying the effect of increased blood flow and blood oxygenation of the specific region of the brain [6]. An MRI is performed by exposing the human body to a strong magnetic field. The strength of the magnetic field (~ 1.5 tesla) causes the proton in each hydrogen atom nucleus (found mostly in water and fat molecules) to align with the magnetic field. A radio frequency pulse is then directed at the body that causes the protons to snap out of their alignment with the magnetic field. As the protons move back to their original positions, they emit radio frequency signals that can be detected by the MRI machine and interpreted to create three-dimensional images [7]. The most useful aspect of an MRI is its ability to form 3D images of the

body that can be viewed from any direction, giving clinicians a way to understand what is happening in the body non-invasively.

1.2.2 Positron Emission Tomography (PET)

Positron emission tomography (PET) is used for measuring the metabolic activity of the cells in the body. This technique produces images of the body's biochemistry, which is fundamentally different from other techniques that produce images of the body's anatomy [8]. To perform a PET scan, the patient is first injected with a radiopharmaceutical or "radioactive tracer". After injection, the scan is delayed anywhere from a few seconds to a few minutes to allow the radio-isotope to transport throughout the area under test. As the radio-isotope decays, it emits a positron which travels a small distance before annihilating with an electron. The annihilation of a positron and electron emits two high-energy photons (511 keV) that propagate in almost opposite directions [9]. The photons emitted are gamma rays which can be detected by the scanning device that surrounds the patient. A computer then analyzes the collection of gamma rays to create a map of the area under test. The amount of radiopharmaceutical collected in the tissue reflects how brightly the tissue will appear on the computer generated image, indicating the level of tissue function [10].

1.2.3 X-Ray Tomography¹

X-rays have been used world-wide since their discovery in 1895 by Rector Wilhelm Conrad Roentgen [11]. To obtain an X-ray image, X-rays are generated from a source and directed towards the patient, where they pass through the body to be detected by a

¹ The information in this section is found in reference [27].

film or ionization chamber on the opposite side of the body. The size of the area exposed to X-rays can be regulated using a collimator to avoid exposing other parts of the body to unnecessary radiation. When the X-ray is completed, there is a contrast in the image due to the attenuation of the X-rays through different tissues in the body. Materials, such as bone, highly attenuate the X-rays and appear white on the X-ray image whereas tissue attenuates the X-rays less and appears darker. If the area being X-rayed is complex, then X-ray computed tomography (CT) is employed. In X-ray CT, the source and detector rotate around the patient. The collection of 1D images from different angles can then be combined to generate a 2D image with a high spatial resolution ($\sim 1\text{mm}$).

1.3 Overview of Functional Near-Infrared Spectroscopy (fNIRS)

Non-invasive near-infrared spectroscopy (NIRS) was initially used to study cerebral oxygenation and muscle oxidative metabolism. This followed the groundbreaking work of Frans Jöbsis who was the first to publish findings on in vivo NIRS [12]. Most of his work was performed from 1977 to 1985, the time between his first publication in *Science*, and his first grant from the National Institute of Health (NIH) [13]. The work was groundbreaking because before fNIRS, conventional imaging techniques explored the body with particles and waves, which underwent very little scattering within the body. As a result, scattering had been viewed as an obstacle to imaging for a long time [14].

In modern research, fNIRS medical imaging methods have been established to create non-invasive methods of studying the human body. fNIRS methods are implemented by exposing parts of the body to visible or near-infrared light [15], and monitoring the scattering and absorption of the different frequencies from multiple detector sources. Unlike other medical imaging methods that rely on large, expensive

instruments to form images, the equipment for fNIRS methods can be quite portable and inexpensive (note that fNIRS imaging monitors the inside of the body, but does not generate images like MRI and PET, therefore it is not used as a replacement for those tests). fNIRS methods are designed to simply monitor specific molecules within the body and no internal changes need to be made to the subject. Infrared light is absorbed by water, as well as oxygenated and deoxygenated hemoglobin, as shown in the absorption spectra of Figure 1.1.

FIGURE 1.1 - ABSORPTION SPECTRUM IN NIR WINDOW [16]

No alteration of these substances is required to enhance or affect detection. The amount of backscattered light of frequencies in the optical window that is not absorbed can be detected and used to determine any changes in the concentration of blood chromophores (oxy and deoxy hemoglobin) [17]. This is simpler than other methods such as MRI or PET. MRI uses expensive instrumentation to create the necessary magnetic fields for imaging, and PET requires the use of a radioactive dye.

Understanding of fNIRS requires knowledge of the properties of infrared light and how it interacts with the human body. When light from the near-infrared (NIR)

spectrum is directed towards the body, the photons from the NIR light scatter based on the physical properties of the tissue being illuminated within the body. Photons from different NIR wavelengths are absorbed in different layers of tissue. These absorbing tissues can be skin, bone, the brain, or other tissues. Some of these photons however, are not absorbed at all. They are scattered and reflected out of the body following specific scattering patterns that are dependent on the type of tissue causing the scattering [18]. The backscattered photons can then be detected by photo-detectors, and information about the absorption properties of the tissue can be collected.

With this data collected, the spectra of light that are absorbed are used to determine what tissues or substances are absorbing the light. It has been found that blood chromophores of oxygenated and deoxygenated hemoglobin absorb the most NIR light, and water is virtually transparent to it. With this information, it is possible to calculate amplitude changes in blood chromophore concentrations from the backscattered portion of NIR light [18]. Using fNIRS, recent studies on exposed brain tissue have shown that brain activity begins with a decrease in hemoglobin oxygenation followed by consistent hemoglobin oxygenation, making fNIRS useful in monitoring the brain [19].

fNIRS is similar to computed tomography (CT) in that they both expose the body to electromagnetic radiation. However, fNIRS does so with a much lower level of energy to ensure that there is no adverse tissue damage as a result. The most important aspect of fNIRS is that it operates at the red edge of the visible light spectrum, allowing frequencies from the 600-900 nm range to probe deeply into the body before they are absorbed. This is an ideal frequency range for probing the body because at longer wavelengths the absorption of water greatly increases, and at shorter wavelengths, blood

dominates the absorption. Operating outside of the 600-900 nm spectra is ineffective because water and blood absorb too much light [20]. This can be clearly shown in Figure 1.1. The range between 700-900 nm is commonly referred to as the “optical window” into the body. Within this range, light travels a number of centimeters into the body and retains adequate amplitude to still be detected, whereas other wavelengths are only useful up to a few millimeters [17].

Using fNIRS as an imaging technique to measure the level of neural activity in the brain is possible because of the neurovascular coupling theorem. This theorem states that there is a “relationship between local neural activity and subsequent changes in cerebral blood flow” [21]. Therefore, when particular parts of the brain are activated, the local blood volume in the area changes rapidly. Along with the local blood volume changing, the optical properties and electrochemical properties change as well. In particular, oxygenated and deoxygenated hemoglobin become visible in the NIR range and a change in concentration can be measured. Since most tissues absorb very little energy at these wavelengths, the surrounding tissue becomes transparent when using this technique. However, the oxygenated and deoxygenated hemoglobin absorb enough energy to make them visible. The most common approach is to calculate the ratio of oxygenated hemoglobin to blood volume [22].

1.4 Scattering²

To better understand fNIRS, it is important to know how photons are scattered within the body. There are essentially three different forms of transmission that can take place: unscattered, forward-scattered, and back-scattered. Unscattered photons arise when a

² The information in this section is found in references [23] and [28]

photon does not come in contact with any tissue and simply passes directly through the body. When this occurs, the optical path length remains the same as the physical distance between the entry and exit points of the photon. A forward-scattered photon arises when the photon changes directions from its original angle of incidence into the body, but still exits opposite from its entry point. Here the path length of the photon becomes longer than that of an unscattered photon. Lastly, when a photon enters the body and is scattered, but exits the body from the same side it entered, it is considered to have been back-scattered. As mentioned earlier, the sensor implemented for the wireless system takes advantage of back-scattered NIR light. For this case, the LED and photodiode can be attached to the same side of the body, allowing for a simpler design. Shown in Figure 1.2 is a graphical example of the three methods of scattering.

FIGURE 1.2 - GRAPHICAL REPRESENTATION OF THE THREE TYPES OF PHOTON SCATTERING

It is clearly shown how the photons that comprise the NIR beam are individually scattered according to one of these three methods of scattering.

Aside from the ways in which photons can be scattered, there are two additional characteristics of scattering: inelastic and elastic. In inelastic scattering, energy at different wavelengths is emitted as the excited molecules revert to one of several other states as the incident energy is absorbed by the scatterer. In elastic scattering, there is no

energy loss so the energy simply moves in a different direction than that of the energy coming in. When using NIR light with tissue, it is possible for both elastic and inelastic forms of scattering to arise although most research has involved elastic scattering.

1.4.1 Rayleigh Scattering

When scattering occurs due to very small particles of radius r , that are much smaller than the wavelength λ , it is known as Rayleigh scattering. In fNIRS, Rayleigh scattering can result from the NIR light being scattered by individual atoms found within the body. Here the particles are exposed to a uniform electric field E_O , and because of this the particle acts as a dipole moment, ρ_m , defined as:

$$\rho_m = \chi E_O \quad \text{Eq. 1}$$

In this definition, χ represents the ability of the scatterer to be polarized. When the scatterer is of a spherical shape, and n is the refractive index, χ can be defined as:

$$\chi = \left(\frac{n^2 - 1}{n^2 + 2} \right) r^3 \quad \text{Eq. 2}$$

Eq. 1 and Eq. 2 can then be combined to redefine the dipole moment to include the polarizability of the scatterer as seen below:

$$\rho_m = E_O \left(\frac{n^2 - 1}{n^2 + 2} \right) r^3 \quad \text{Eq. 3}$$

The electric field of the scattered wave can then be used to derive an expression for the scattered intensity I_s , at a distance x_s , from the scatterer at a scattering angle of θ , due to the incident intensity I_O . This gives rise to the Rayleigh equation for describing a single scatterer, shown below:

$$\frac{I_s}{I_O} = \frac{8\pi^4 r^6}{x_s^2 \lambda^4} \left(\frac{n^2 - 1}{n^2 + 2} \right) (1 + \cos^2 \theta) \quad \text{Eq. 4}$$

Eq. 4 shows that this type of single scatterer is not strong because the particle radius is a sixth power that quickly decreases with wavelength as a function of λ^{-4} . Shown below in Figure 1.3 is an example of Rayleigh scattering.

FIGURE 1.3 - EXAMPLE OF RAYLEIGH SCATTERING

Rayleigh scattering is considered to be a form of elastic scattering because the energy from the scattered photons does not change. When photons change energies during scattering, it is known as Raman scattering.

1.4.2 Debye Scattering

Particles can be considered as a collection of point sources when the particles are larger than they are in Rayleigh scattering, but are still smaller than λ . In this case, each particle acts as a dipole that reradiates electromagnetic energy. In fNIRS, Debye scattering can be caused by groups of smaller particles clumped together, such as molecules. The scattered electromagnetic fields will interfere with each other due to the relative phase for each field. The phase factor can be defined as:

$$\Gamma = \frac{3}{k^3} (\sin(k) - k \cos(k)) \quad \text{Eq. 5}$$

The relationship between particle radius, wavelength, and scattering angle are attributed to k by:

$$k = \left(\frac{4\pi r \sin(\theta/2)}{\lambda} \right) \quad \text{Eq. 6}$$

With Eq. 5 and Eq. 6 the overall scattered intensity can be defined as follows:

$$\frac{I_s}{I_0} = \frac{8\pi^4 r^6}{x_s^2 \lambda^4} \left(\frac{n^2 - 1}{n^2 + 2} \right) (1 + \cos^2 \theta) \Gamma^2 \quad \text{Eq. 7}$$

When these Debye conditions are met, stronger and more forward-directed scattering takes place and the intensity of the scatter decreases approximately as λ^{-1} .

1.4.3 Mie Scattering

If scattering particles have radii larger than λ , then Rayleigh and Debye scattering are overtaken by Mie scattering. In fNIRS, Mie scattering can be caused by blood cells or other objects of considerable size with respect to wavelength. Mie scattering accounts for scattering events arising from within the particle. For N spherical scatterers, the scattered intensity is defined as:

$$\begin{aligned} \frac{I_s}{I_0} = \frac{N\lambda^2}{8\pi^2 x_s^2} & \left\{ \left[\sum \frac{2n+1}{n(n+1)} (a_n \gamma_n(\cos \theta) + b_n \tau_n(\cos \theta)) \right]^2 \right. \\ & \left. + \left[\sum \frac{2n+1}{n(n+1)} (b_n \gamma_n(\cos \theta) + a_n \tau_n(\cos \theta)) \right]^2 \right\} \end{aligned} \quad \text{Eq. 8}$$

Where a_n and b_n are scattering coefficients and γ_n and τ_n are angular dependent functions [23]. Shown below in Figure 1.4 is an example of Mie scattering.

FIGURE 1.4 - EXAMPLE OF MIE SCATTERING

The larger the scattering object, the more dominant the front lobe becomes. That means the light waves exiting the opposite side of the incident light direction become condensed, and the front lobe becomes narrower. Figure 1.5 shows this in more detail.

FIGURE 1.5 - EXAMPLE OF LARGE OBJECT MIE SCATTERING

It is also important to note that Mie scattering is not exceedingly wavelength dependent.

1.5 Three Types of fNIRS Imaging

There are three main types of NIR imaging currently in use [5]. These are continuous wave (CW), frequency domain (FD), and time resolved (TR). The type implemented for the instrumentation described in this thesis is the CW method where NIR light is directed at a constant intensity level during the measurement sequence, and the detected signal is a decayed version of the input signal. With the FD method, the input signal is a sinusoidal signal at a desired frequency and the output signal reveals a change in amplitude and phase. With the TR method, a picoseconds pulse is applied and the detected signal is a longer signal that decays over time. Each of these methods has different advantages and disadvantages in various applications.

1.6 Modified Beer-Lambert Law (MBLL)³

Infrared radiation is produced by an infrared LED, and the scattered output signal is measured with a photodiode. The change in magnitude of the light will indicate changes in hemoglobin concentrations due to the absorption of the light. This is calculated using the Modified Beer-Lambert Law (MBLL), which states that there is a relationship between the absorption of light and the material which is absorbing the light.

³ The information in this section is found in reference [26]

The Modified Beer-Lambert Law is based on how oxygenated and deoxygenated hemoglobin absorb NIR light and provides a practical description of optical attenuation in highly scattering mediums. This allows for changes in chromophore concentrations to be quantified. The Modified Beer-Lambert Law is shown below:

$$OD = -\log\left(\frac{I}{I_o}\right) = \epsilon CLB + G \quad \text{Eq. 9}$$

The variables in the MBLL represent the following values: optical density (OD), incident light intensity (I_o), detected light intensity (I), extinction coefficient of the chromophore (ϵ), distance between entering light position and detected light position (L), path and length factor accounting for increased photon path length brought on by tissue scattering (B), and factor accounting for measurement geometry (G).

It is important to understand that a change in chromophore concentration will cause the detected intensity to change. When concentration changes, the extinction coefficient ϵ and distance L do not change, and it is assumed that B and G remain constant. Therefore we are able to rewrite the initial MBLL with the log base e convention, as:

$$\Delta OD = -\ln\left(\frac{I_{Final}}{I_{Initial}}\right) = \epsilon \Delta CLB \quad \text{Eq. 10}$$

Where $\Delta OD = OD_{Final} - OD_{Initial}$ represents the change in optical density, I_{Final} and $I_{Initial}$ represent the measured intensities before and after the concentration changed, and ΔC is the change in concentration. L is known from the emitter and detector separation distance, ϵ is specific to the type of chromophore, and B has been previously calculated for different types of tissues. Therefore the change in chromophore concentration can be

calculated from the given extinction coefficient. However, if we want to use the above condensed MBLL to account for independent concentration changes in oxygenated and deoxygenated hemoglobin, then we must rewrite the equation to account for both chromophores as seen below (where λ represents a specific wavelength):

$$\Delta OD = (\epsilon_{HbO}^{\lambda} \Delta[HbO] + \epsilon_{Hb}^{\lambda} \Delta[Hb]) B^{\lambda} L \quad \text{Eq. 11}$$

By using the known extinction coefficients of oxyhemoglobin (ϵ_{HbO}) and deoxyhemoglobin (ϵ_{Hb}), and measuring ΔOD at two wavelengths, their concentration changes can be computed from the following equations:

$$\Delta[Hb] = \frac{\epsilon_{HbO}^{\lambda_2} \frac{\Delta OD^{\lambda_1}}{B^{\lambda_1}} - \epsilon_{HbO}^{\lambda_1} \frac{\Delta OD^{\lambda_2}}{B^{\lambda_2}}}{\left(\epsilon_{Hb}^{\lambda_1} \epsilon_{HbO}^{\lambda_2} - \epsilon_{Hb}^{\lambda_2} \epsilon_{HbO}^{\lambda_1} \right) L} \quad \text{Eq. 12}$$

$$\Delta[HbO] = \frac{\epsilon_{Hb}^{\lambda_1} \frac{\Delta OD^{\lambda_2}}{B^{\lambda_2}} - \epsilon_{Hb}^{\lambda_2} \frac{\Delta OD^{\lambda_1}}{B^{\lambda_1}}}{\left(\epsilon_{Hb}^{\lambda_1} \epsilon_{HbO}^{\lambda_2} - \epsilon_{Hb}^{\lambda_2} \epsilon_{HbO}^{\lambda_1} \right) L} \quad \text{Eq. 13}$$

CHAPTER II

fNIRS SYSTEM OVERVIEW

2.1 Overview of the fNIRS Wireless Imaging System

Medical imaging techniques such as MRI and PET are performed within the confines of a laboratory or clinical setting. This is because the equipment needed for these medical procedures often consumes significant amounts of power and requires interfacing several different components such as computers, monitors, amplifiers, and other necessary medical hardware. However, the most inconvenient aspect of these medical imaging techniques is that they require the patient to remain motionless. The goal of the fNIRS wireless system is to free the subject from direct attachment to the instrumentation and allow medical research to be performed in a less restrictive manner.

Allowing medical researchers to explore and study the human body with a small, portable wireless system will give them the ability to understand how the human body reacts under various situations that could not be explored with existing, non-portable imaging instrumentation. Without the confines of a laboratory, medical researchers and scientists can study the human body when it is undergoing types of stress that are not possible when the patient is confined by the requirements of other imaging methods.

The following chapters will describe in detail each component of the portable wireless fNIRS system and the integration of these components. The sensor design will be described, followed by the data processing and control circuitry, phantom testing, and then the wireless communication system.

CHAPTER III

SENSOR DESIGN

3.1 Sensor Design Overview

The optical imaging sensor consists of two elements: an Epitex NIR LED (See APPENDIX A) that emits three different wavelengths of light: 730, 805, and 850 nm, and an OPT101 photodiode (See APPENDIX B). The three wavelengths available in the LED are controlled by the application of current to individual pins associated with each wavelength. Using this configuration, specific wavelengths can be turned on and off allowing the user to change which compounds are to be probed in the body by switching to the appropriate NIR wavelength.

3.2 Sensor Development

The overall sensor development process was developed in such a way that it could easily be modified in the future to fit custom applications. As will be explained in the following sections, the use of SolidWorks™ allows for custom shaped sensors to be built that can accommodate several LEDs and photodiodes with customized separation distances for specific applications.

3.2.1 Sensor Mold

The design for the sensor mold was developed using SolidWorks™. This allowed the mold to be crafted to exact specifications and to be modified in the future if needed. Shown below in Figure 3.1 is the mold developed in SolidWorks™.

FIGURE 3.1 - OPTICAL SENSOR MOLD DEVELOPED IN SOLIDWORKS™

With a finished SolidWorks™ file for the mold, we were then able to print a 3D plastic mold using a 3D printer. The 3D printer used was a Dimension BST which creates 3D objects by stacking many 2D layers of acrylonitrile butadiene styrene (ABS), which is an amorphous thermoplastic that is very resistant to stress and cracking [24]. Shown below in Figure 3.2 is the printed 3D optical sensor mold.

FIGURE 3.2 - OPTICAL SENSOR MOLD

3.2.2 Sensor Fabrication

The sensor is fabricated by installing all the components into the plastic mold in the shape needed for the particular application. The source (LED) and detector (photodiode)

are properly wired and connected to I/O ports along the outside of the sensor mold. The mold is then injected with a silicone rubber compound and placed in an oven at 60 degrees Celsius for approximately 8-12 hours. Once it cures, the plastic mold is removed and we are left with a flexible, silicone rubber optical imaging sensor.

3.2.3 Power Management

Sensor power distribution is currently managed by the main control board. It receives +5 V to power the photodiode and receives +10 V to power the three LED wavelengths. The +10 V is shared in parallel by the three individual devices in the LED because typically, only one device is powered at a time. Resistors are used to create voltage dividers that reduce the +10 V to the appropriate operating voltage for each device. The required operating voltages are shown below in Table 3.1 along with the amount of current drawn by each LED wavelength device.

TABLE 3.1 - LED OPERATING VOLTAGES FOR EACH NIR WAVELENGTH (SEE APPENDIX A)

LED Wavelength	730 nm	805 nm	850 nm
Operating Voltage	7.6V	6.4V	5.6V
Current	30mA	14mA	9mA
Resistance	330 Ω	560 Ω	750 Ω

The resistance values shown in the above table are the individual resistances that are combined with 1K Ω resistors to create the voltage dividers used to achieve the LED operating voltages. Shown below in Figure 3.3 is the schematic for the LED switches.

FIGURE 3.3 - SWITCHING CIRCUIT FOR THE DIFFERENT LED WAVELENGTHS

1KΩ resistors are used in each of the three voltage dividers along with three other resistors that provide the correct operating voltages for each of the LEDs. The power for each LED is sent over a ribbon cable to the corresponding pins on the LED and photodiode. Shown below in Figure 3.4 is the internal wiring of the LED and photodiode.

FIGURE 3.4 - INTERNAL PHOTDIODE AND LED WIRING

The photodiode only requires +5 V to operate and to be grounded. The other pins apply to different applications for the photodiode and are therefore unused. The output voltage of the photodiode (Pin 5) is sent to the variable gain amplifier (VGA) for amplification before reaching the analog to digital converter. For the LED, each voltage from the switching circuit is fed to the corresponding pins for each wavelength. Table 3.2 below shows the pin configuration for each wavelength.

TABLE 3.2 - PIN CONFIGURATION FOR EACH LED WAVELENGTH

Wavelength (nm)	Power Pin	Ground Pin
730	Pin 2	Pin 4
805	Pin 1	Pin 5
850	Pin 8	Pin 6

The sensor itself is quite small when only housing one photodiode and one LED. In this single unit configuration it measures 2 x 0.8 x 0.4 inches. Shown below in Figure 3.5 is a completed optical sensor. The emitter and detector are spaced about 1.25 inches apart, however increasing the separation distance between them will increase penetration depth into the area under test.

FIGURE 3.5 - THE OPTICAL SENSOR

Eventually the system will be able to encompass several photodiodes and LEDs across multiple sensors, depending on the specific application required. Shown below in Figure 3.6 is an example developed in SolidWorks™ of how the sensors can be modularized to create an optical sensing array.

FIGURE 3.6 - OPTICAL SENSING ARRAY

An optical sensing array can provide better overall data acquisition over larger test areas because it allows for data to be collected from many different areas simultaneously.

CHAPTER IV

DATA PROCESSING AND CONTROL CIRCUITRY

4.1 Wireless System Data Processing and Control Circuitry Overview

The data processing and control circuitry are a crucial part of the entire imaging system and are carefully designed to work seamlessly with the optical sensor and wireless interface. The data processing and control circuitry are designed to be small and portable. The goal is to keep the circuitry as simple and compact as possible. The core data processing and control of the system is accomplished using the following components:

1. Variable Gain Amplifier (VGA)
2. 8-Bit Analog to Digital Converter (ADC)
3. 4-Bit Synchronous Counter
4. NAND Gate
5. Inverter
6. Flip-Flop
7. 2.4 KHz On-Board Clock
8. MAX232 chip for converting 0-5 V to ± 9 V for serial transmission following the RS232 standard

The next section describes in detail the integration of these components and how each serves an important function in the overall operation of the data processing and control

system. To get a clearer understanding of how the next few sections tie together, a block diagram has been provided below in Figure 4.1.

FIGURE 4.1 - WIRELESS SYSTEM BLOCK DIAGRAM

4.1.1 Variable Gain Amplifier (VGA)

For the variable gain amplifier, a Motorola LM358N dual, low power operational amplifier is used (See APPENDIX C). The variable gain amplifier is used to amplify the voltage output from the optical sensor. It has been characterized using a $2K\Omega$ resistor and 80Ω potentiometer to provide gains from 1 to 40 (output voltages from 0.1 V to 4.0 V with input of 0.1 V). Gain of the system is varied based upon the signal strength associated with the test location and individual tissue characteristics. To compensate for these changes, the output signal of the sensor can be amplified by a gain that is determined from the experimental conditions. This allows for accurate results to be obtained from a wide range of subjects rather than just from the ones whose body

characteristics most conveniently work with the system. The amplified signal from the optical sensor is then fed in as the input to the ADC. This is the main input for data processing.

4.1.2 8-bit Analog to Digital Converter (ADC)

For the analog to digital converter (ADC), a Texas Instruments TLC0831CP successive-approximation ADC is used (See APPENDIX D). The ADC has an 8-bit resolution to quantize input voltages from the amplifier between 0-5 V to a serial output of values ranging between 0-255. The TLC0831CP has two modes of operation. Without control circuitry, the ADC can be set to continuously read voltages and output serial bit streams by grounding the chip select pin (CS'). For our application however, sampling the sensor output at a user defined interval is more appropriate than reading every sensor output value. To achieve this sampling effect, the data processing circuitry regulates the CS' pin transitions, thereby allowing us to sample the sensor output each time CS' is forced low. This will be explained in detail in the descriptions of the rest of the circuitry. Once a reading is taken, the serial output is sent to the MAX232 chip which converts the 0-5 V bit stream into a ± 9 V signal that can be sent to the wireless development board via the RS232 standard.

4.1.3 4-Bit Counter

For the counter, a Philips 74HC161N pre-settable, 4-bit synchronous counter with asynchronous reset is used (See APPENDIX E). The counter is used to control the read command to CS'. By default, the counter cycles from 0 to 15 as long as the master reset pin (MR') is set high. When the counter reaches 15, it then signals a one clock cycle wide high pulse from the terminal count pin (TC). TC is used to control other circuitry

by signaling the end of the count cycle to another chip. However, counting from 0-15 is not suitable for controlling CS' on the ADC for this application. Therefore, an alternative signal is provided to replace TC.

Once CS' transitions from high to low, the ADC starts its conversion by inserting a low start bit, then 8 bits of data. This means that to get the ADC to perform its full conversion correctly, CS' must remain low for a period of 9 clock cycles and then go high for one clock cycle to substitute as the stop bit (the ADC does not provide its own stop bit, so a high stop bit was added at the end of the conversion). The start and stop bits are necessary for the wireless transmission so that the receiving computer is aware of when data is being sent and when it has completed sending. However, due to delays from the setup time required by the ADC, CS' needs to remain low for 10 clock cycles (a timing diagram is provided further in the chapter). To accomplish this, the four flip-flop outputs of the counter (Q0-Q3) are fed into a NAND gate. The Q0-Q3 flip-flops are output from the counter to show what the current value of the counter is. Table 4.1 below shows their outputs from 0-15.

TABLE 4.1 - FLIP-FLOP OUTPUTS OF THE COUNTER

Count	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Q0	0	1	0	1	0	1	0	1	0	1	<u>0</u>	1	0	1	0	1
Q1	0	0	1	1	0	0	1	1	0	0	<u>1</u>	1	0	0	1	1
Q2	0	0	0	0	1	1	1	1	0	0	<u>0</u>	0	1	1	1	1
Q3	0	0	0	0	0	0	0	0	1	1	<u>1</u>	1	1	1	1	1

4.1.4 NAND Gate and Inverter

For the NAND gate, a Texas Instruments SN74HC20N dual, 4-input positive NAND gate is used (See APPENDIX F). The NAND gate continuously outputs a high signal state on its output until all four of its inputs are "1". When this occurs, the NAND gate then

outputs a low signal state until at least one of its inputs becomes a “0”. In order to get the NAND gate to output a high signal state again after one clock cycle, the counter needs to be reset. To reset the counter, the MR’ pin on the counter must receive a high to low transition. By sending the output of the NAND gate to the MR’ of the counter, the counter will be reset every time the NAND gate receives all “1’s” and the NAND gate will then output a low signal again. In order to achieve all “1’s” in the NAND gate before the counter reaches 15, an inverter is used to invert the Q0 and Q2 flip-flop signals before they enter the NAND gate. The inverter used is an ON Semiconductor MC14049UBCPD hex inverter (See APPENDIX G). The binary representation for ten is 1010, so by inverting Q0 and Q2, the NAND gate will see 1111 when the counter reaches ten. With the NAND gate receiving all “1’s”, the counter will be forced to reset. Shown below in Table 4.2 are the outputs for the NAND gate with Q0 and Q2 inverted.

TABLE 4.2 - NAND GATE OUTPUTS WITH Q0 AND Q2 INVERTED

Count	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Q0'	1	0	1	0	1	0	1	0	1	0	<u>1</u>	0	1	0	1	0
Q1	0	0	1	1	0	0	1	1	0	0	<u>1</u>	1	0	0	1	1
Q2'	1	1	1	1	0	0	0	0	1	1	<u>1</u>	1	0	0	0	0
Q3	0	0	0	0	0	0	0	0	1	1	<u>1</u>	1	1	1	1	1
NAND	1	1	1	1	1	1	1	1	1	1	<u>0</u>	1	1	1	1	1

4.1.5 Flip-Flop

For the flip-flop, a Motorola MC74HC74A dual, D flip-flop with set and reset is used (See APPENDIX H). The flip-flop is used to create the actual CS’ signal and it changes state on the rising edge of each clock cycle. But instead of feeding the flip-flop an actual clock signal, the output of the NAND gate is sent to an inverter so a single low to high pulse reaches the flip-flop every 10 clock cycles. When the flip-flop receives the first

pulse, it goes to a high state. This high state is fed back into the flip-flop as in input, and when it receives the next pulse from the inverted NAND gate output, it will flip to its opposite state, which would be low. It is important to note that the current state of the flip-flop is continuously output from its Q1 pin (this is different than the Q1 pin on the counter). This signal is high for 10 clock cycles and then low for 10 clock cycles. This repeats continuously until the entire board is powered down. The low for 10 clock cycles, high for 10 clock cycles signal is fed straight into CS' on the ADC providing it the necessary window to convert 8 bits worth of data with a start bit and our added stop bit, and then wait another 10 clock cycles before the next conversion. This provides a sampling rate of 120 samples per second at 2400 baud.

4.1.6 On-Board Clock

For the clock, a National Semiconductor LM555CN timer is used (See APPENDIX I). The on-board clock generates a 2.4 KHz clock that matches the 2400bps baud rate used to communicate with the wireless system. To accomplish this, the LM555CN was set up as a 50% duty cycle oscillator, which allowed for the development of an accurate clock signal. To achieve 2.4 KHz, the required resistor values were determined to be 30062.53Ω and 12725.65Ω . With these resistor values at a tolerance of $\pm 0.05-0.10\%$, it is possible to get within 0.2% of the 50% duty cycle. Due to the extended wait period for custom resistors to be manufactured, two sensitive trimmer potentiometers are being used for the clock circuit.

4.2 Circuit Schematic

The layout for all of the integrated circuitry is rather complex. To gain a better understanding of how each chip functions with the rest of the board, a schematic has been

within the control and data processing circuitry. The timing diagram is shown below in Figure 4.3 (Note that the ADC Data 1 and ADC Data 2 signals demonstrate two separate conversions, but serve to show how the stop bits are added when the conversion ends in a 1 or a 0).

FIGURE 4.3 - TIMING DIAGRAM

4.4 Altium Designer™ and Board Fabrication

Once all of the circuitry was designed and tested, a printed circuit board (PCB) was laid out for the components. This was important not only to make the system portable and smaller, but also to remove unwanted noise in the system arising from all the stripped wires and breadboard connections. To develop the printed circuit board layout, Altium Designer™ was used. The software allows all of the component pieces to be wired together by creating a schematic from a large parts data base. Shown below in Figure 4.4 is the schematic for the data processing and control circuitry board developed in Altium Designer™.

FIGURE 4.4 – DATA PROCESSING/CONTROL CIRCUITRY BOARD ALTIUM DESIGNER™ SCHEMATIC

Once the schematic is completed, all of the signal routing must be performed on the printed circuit board. Altium Designer™ automatically routes all of the signal traces from the schematic so that none of them cross and to ensure that all connections are accounted for. Shown below in Figure 4.5 is the final layout of the printed circuit board generated by Altium Designer™.

FIGURE 4.5 - ALTIUM DESIGNER™ PRINTED CIRCUIT BOARD LAYOUT

32

CHAPTER V

WIRELESS COMMUNICATION

5.1 Wireless Communication Overview

The wireless communication for the transmission of data from the imaging sensor to the base station computer is achieved using two Radicom WHM900 RF antennas mounted on development boards [25]. The sending and receiving antennas communicate on a 915.02MHz frequency, which lies in the License-Free ISM Band (900-928MHz). They communicate with a baud rate of 2400bps and have a communication range of approximately 300 to 500 feet. This range is more than acceptable for the applications that the imaging system is designed for. The Radicom WHM900 development board was used for initial system development because it allowed for easy communication with the base station computer. The provided RS-232 cable allows for direct communication with the module via HyperTerminal, and also allows the module to send data to MATLAB™. Shown below in Figure 5.1 is an image of the WHM900 antenna and communications module.

FIGURE 5.1 - RADICOM WHM900 ANTENNA [25]

5.2 Wireless Data Links

The WHM900 comes equipped with the ability to establish three different types of wireless data links. The first is Point-to-Point Operation, which allows the user to establish single, or multiple point-to-point locations by setting different channel IDs, frequencies, and speeds. The second is Auto-Link Operation, which forces the sending and receiving modules to maintain a point-to-point connection automatically. The third is Point to Multi-Point Broadcasting, which allows for a Master module to broadcast data to multiple remote Slave modules. For our specific application, the Auto-Link Operation wireless data link was chosen because we only had two communicating modules and one communication link. One advantage of using the Auto-Link Operation is that if there is a power outage or the link is lost due to temporary interference, the modules will automatically detect the lost data link and automatically re-establish a connection. Also, once the modules are designated as sender and receiver through commands in HyperTerminal, the modules automatically establish a connection at power-on. Shown below in Figure 5.2 is the transmitting wireless development board.

FIGURE 5.2 - TRANSMITTING WIRELESS MODULE

5.3 Configuring the Modules

HyperTerminal is used to communicate with the WHM900 modules through a series of predefined terminal commands. To establish an Auto-Link connection between two modules, one module is set up for Answer Mode (receiver) and the other for Originate Mode (sender). To do so, the command “ATS0=1&W” is sent to one module and the command “ATS0=2&W” is sent to the other module. Once this is completed, the Auto-Link Operation setup is complete and the modules are ready to communicate. There are also several default settings that can be changed such as the operating frequency, baud rate, and transmit level. These adjustments are made by sending the module other terminal commands. All of the settings are stored in Non-Volatile Memory (NVRAM) so that if the module is powered down, it still retains all of its current settings. Therefore, setup is only required one time unless changes are desired. To change a setting, “+++” is entered in HyperTerminal and the module enters *On Line Command Mode* and the change commands can be entered. After settings have been changed, to return to *On Line Data Mode*, “ATO” must be entered in HyperTerminal.

5.4 MAX232 and Serial Communication

Currently, the data processing circuit utilizes a MAX232 chip to interface the system control circuitry with the wireless board. This chip is essential to bridge the communication gap because the data processing board and the wireless modules communicate with signals of different voltages. The data processing board’s data signal that is sent to the wireless board is a 0-5 V signal. However, the communication link between the data processing board and wireless board is an RS-232 cable. The RS-232 standard requires signals that are ± 9 V, so transmitting a 0-5 V signal over an RS-232

cable is insufficient. The MAX232 chip takes the 0-5 V bit stream from the ADC and converts it to ± 9 V before sending the data to the wireless board. Eventually the need for the MAX232 chip will be phased out as the wireless circuit card is mounted directly to the circuit board, and the entire data processing system is made as a field-programmable gate array (FPGA).

CHAPTER VI

PHANTOM DEVELOPMENT AND SYSTEM CHARACTERIZATION

6.1 Phantom Development Overview

In order to test our system response, a series of phantom test structures was prepared. A phantom is a synthetic model created to simulate the desired response of the fNIRS sensor to changes in oxy and deoxy-hemoglobin. Phantoms range in complexity from simple models of biological tissue, to complex models designed to accurately emulate the chemical composition of the human body. The more complex the data obtained from an imaging system, the more accurate the phantoms must be to properly test all the different components of the biological system.

After the development of any new medical imaging hardware, it is important to understand it thoroughly and perform controlled tests on the new equipment to ensure proper functionality and consistency of results. Although it is important to eventually perform tests on live subjects, it is also necessary to characterize the system using phantoms to ensure that the system is safe and that accurate results will be achieved when in vivo testing is conducted. The most useful aspect of phantoms is that they permit functional characterization of the system because they can be created to very specific standards with known concentrations of chemicals. Therefore, the response of the imaging system can be characterized when the exact properties of the phantom are known. Phantoms play an integral role in all medical imaging systems because they provide help in the development process, and ensure that medical systems do not cause adverse effects to people.

The Epitex LED and OPT101 photodiode implemented for the sensor are a good pairing for implementing fNIRS. This is partly due to the fact that these components are relatively inexpensive and effective in fNIRS applications. The 8-bit ADC provides 256 bits of resolution over 0-5 V so voltages can be detected at approximately 0.02 V intervals without amplification, which provides accurate quantization resolution. With a higher resolution ADC, more accurate data could be obtained however 8-bit resolution is currently sufficient for this specific application.

The goal of the system characterization was to verify that the overall system will respond to a variation in simulated test conditions. The sensor system was tested on phantoms and the data presented here is used to characterize system functionality, but is not representative of any particular biological system.

6.2 Creating the Phantoms

The phantoms used for our initial characterization required four components. These four components are listed below in Table 6.1. Silicone (base plus curing agent) is used as the structural base for the phantoms. Agents were also added to provide scattering and absorption characteristics.

TABLE 6.1 - THE FOUR MAIN ELEMENTS OF A PHANTOM

Phantom	Component
Base	RTV12A
Curing Agent	RTV12C
Scattering Agent	TiO ₂
Absorbing Agent	Carbon Black

A weight ratio of 10:1 of RTV12A:RTV12C is used for the basic silicone form. The components are weighed and added into the RTV12A base compound. This compound is thoroughly mixed prior to curing.

The mold used to define the phantom shape, shown in Figure 6.1, has four 4cm x 6cm x 4cm openings and is constructed of Plexiglas to avoid reaction with the curing agent. The phantom mixture is carefully poured into the mold and set aside to cure for 24 to 48 hours at room temperature.

FIGURE 6.1 - PLEXIGLAS PHANTOM MOLD

6.3 System Characterization⁴

Phantom design and production was completed in the Rowan University Mechanical Engineering Material Laboratory. The following sections describe in detail the phantom composition and the data obtained from testing with the phantoms.

6.3.1 Testing for Backscattered Light

The first test was performed on a phantom that contained no scattering compound or absorber. This is designated as a “clear” phantom. As shown schematically in Figure 6.2, the clear phantom is placed on a flat surface and the NIR sensor is positioned to direct the

⁴ All phantom testing was performed with the pre-amp set to a gain of one.

stimulus from the NIR LED into the body of the phantom. The OPT101 photodiode detector responds to any backscattered light.

FIGURE 6.2 - CONTROL TEST SETUP CONFIGURATION WITH A CLEAR PHANTOM

Data were obtained with the phantom positioned on a black surface and then on a white surface. The entire test setup was encased in an opaque enclosure. It was expected that the detected signal would be larger when the white surface was beneath the phantom. At all three wavelengths, the system performed as expected. For this characterization, the 805 nm wavelength was chosen as a reference. 805 nm is the crossover point in absorption for oxy and deoxy-hemoglobin (See Figure 1.1) and thus represents the mid-point of the NIR spectrum for the targeted application. At 805 nm the following data was obtained as shown in Table 6.2.

TABLE 6.2 - DATA COLLECTED AT 805 NM

$\lambda = 805 \text{ nm}$	
Black Surface	White Surface
0.291 V	0.735 V

The voltage values obtained from the sensor at 805 nm are indicative of the reflection of the NIR signal from the surfaces through the clear phantom and are intended to demonstrate system functionality.

6.3.2 Varying Levels of TiO₂

For testing the system response to varying levels of absorbing compound, an optimal amount of scatterer (TiO₂) was determined empirically. The goal is to contain the NIR signal completely within the phantom. Testing was performed with the goal of developing phantoms that would scatter the NIR signal in a similar manner to biological tissue and most accurately demonstrate the correct functionality of the sensor and circuitry. To gain an understanding of how the phantoms would perform under testing, three additional phantoms were created each with a different quantity of titanium dioxide (TiO₂) distributed throughout the silicone molds. The four quantities chosen were: 0g (the clear phantom), 1g, 2g, and 3g TiO₂. By using a silicone phantom with no TiO₂ as a control, we were able to see how much backscattered light would be produced by each different phantom as the quantity of TiO₂ was increased with no absorber added. The phantom testing was again performed on both black and white surfaces to see how much light was being backscattered by the TiO₂ or by the surface that the phantom was resting on (this was also done to determine a correct thickness for the phantoms). The sensor and phantom were also shielded from ambient light by being enclosed in an opaque box. Shown below in Figure 6.3 is the test setup configuration for testing on black and white surfaces with varying amounts of TiO₂.

FIGURE 6.3 - TEST SETUP CONFIGURATION FOR VARYING TIO2 CONCENTRATIONS

Using the above configuration, each phantom with a different concentration of TiO_2 was tested at each of the three NIR wavelengths, and the scatterer was spread as homogenously as possible throughout the phantoms (data from the clear phantom is repeated here for comparison). The data collected from these measurements at 805 nm are shown below in Table 6.3.

TABLE 6.3 - VOLTAGE READINGS FOR TiO_2 CONCENTRATIONS ON BLACK/WHITE SURFACES

Wavelength $\lambda = 805 \text{ nm}$			
Surface	Black	White	ΔV
0g TiO_2	0.291 V	0.735 V	0.444 V
1g TiO_2	0.133 V	0.229 V	0.096 V
2g TiO_2	0.044 V	0.060 V	0.016 V
3g TiO_2	0.026 V	0.033 V	0.007 V

The data shown in Table 6.3, on both black and white surfaces, reveals the trend that we anticipated. As the amount of TiO_2 is increased, light is scattered throughout the phantom rather than being directed to and reflected from the underlying surface. As TiO_2 levels increased, ΔV decreased indicating that the underlying surface was decreasingly significant as an influence in the measurement. Because the measurement, ideally, should not be influenced by the environment but only a function of the components of the phantom, ΔV should approach 0. Because we chose not to adjust the gain of the system preamplifier, the compromise for this testing phase was to choose a value of TiO_2 in the phantom that yielded reasonable voltage levels with small ΔV . Consequently, the 2g level of TiO_2 was chosen. This amount of TiO_2 translated into a density of 0.0197 g/cm^3 , which was used for the remainder of the system characterization measurements.

6.3.3 Signal Detection Sensitivity to Different Absorber Concentrations

Finally, the sensitivity of the system to varying levels of absorbing compound was demonstrated. A new set of phantoms was fabricated with the concentration of TiO_2 held constant at 0.0197 g/cm^3 . Carbon black, a compound sometimes used as a pigment in rubber products, was used as the absorber. Two levels of absorption were simulated by adding carbon black to the phantoms in the following quantities: 0.01g and 0.05g.

With the concentration of scatterer in the phantoms at 0.0197 g/cm^3 , it was assumed that the testing surface was only reflecting a minute amount of NIR light, however testing was performed once again on both black and white surfaces for consistency. Measurements of backscattered light were made at each level of added carbon black. At the reporting wavelength, 805 nm, the data shown in Table 6.4 was obtained.

TABLE 6.4 - VOLTAGE RESPONSE AT 805 NM WITH INCREASING AMOUNTS OF CARBON BLACK

$\lambda = 805 \text{ nm}$		
Carbon Black	Black	White
0.01g	0.042 V	0.047 V
0.05g	0.007 V	0.014 V

The choice of carbon black quantities was not adequately fine grained in this experiment. Between 0.01g and 0.05g, ΔV is 0.035 V on the black surface and ΔV is 0.033 V on the white surface, which indicates a strong response to the increased concentration of carbon black.

CHAPTER VII

SYSTEM INTEGRATION AND TESTING

7.1 Wireless Communication Software⁵

Software was developed in MATLAB™ to view and collect the data arriving at the base station computer. There are several different aspects to the software, each designed for taking care of specific tasks. Some of these tasks include the processing of incoming data, plotting incoming data in real time, and data comparison. This section will describe the different software aspects.

7.1.1 Connect.m

In order to communicate with the wireless board receiving all of the sensor data, a connection needs to be established between MATLAB™ and the wireless board. To do this, a serial port object is first defined where the baud rate, number of bytes to read, etc., are all configured. Next, the actual port is opened for communication with the previously defined settings. Then, data are read from the serial port one byte at a time until the number of bytes to read has been reached. All of the data are read in as unsigned 8-bit integers because we are only dealing with values between 0-255. Once the data collection is complete, the serial port is then closed and the connection between MATLAB™ and the wireless board is disconnected. Shown below in Figure 7.1 is the MATLAB™ command window output for connect.m.

⁵ All MATLAB™ code is available in APPENDIX J.

A screenshot of the MATLAB Command Window titled "Command Window". The window has a menu bar with "File", "Edit", "Debug", "Desktop", "Window", and "Help". The command prompt shows the execution of the "connect" script. The output text is as follows:

```
>> connect
Enter the Number of Bytes to Read: 512
Serial Port Connection Established
Serial Port Open for Reading
Press 1 to Begin Reading or 2 to Quit: 1
Reading data please wait...
Data Read Complete
Serial Port Connection Closed
>>
```

In the bottom right corner of the window, there is a small status bar with the text "OVR" and a small icon.

FIGURE 7.1 - CONNECT.M COMMAND WINDOW OUTPUT

7.1.2 Convert.m

The next step after reading all of the data from the serial port is to convert the data into the correct format. This must be done because the ADC outputs its conversions with the least significant bit (LSB) first and the most significant bit (MSB) last, whereas MATLAB™ reads the data in the opposite configuration. To compensate, the bits that are read must be reordered. For example, a binary “11001100” output from the ADC will be interpreted by MATLAB™ as 51 in decimal, when the actual number is 204. By reversing the data to “00110011”, MATLAB™ will then interpret the number correctly as 204. This is performed on every byte using a simple algorithm so that all of the data is correct. Then, each byte is multiplied by 5/256 to get a decimal voltage between 0-5 V from the 0-255 quantization used by the ADC. All the voltages are then plotted to give a visual representation for the information gathered by the sensor. All of the data are then stored in a text file for future reference or immediate analysis. Shown below in Figure 7.2 is the MATLAB™ command window output for convert.m followed by the voltages saved to the text file for a simple test in Figure 7.3.

A screenshot of a MATLAB Command Window. The title bar says "Command Window". The menu bar includes "File", "Edit", "Debug", "Desktop", "Window", and "Help". The command prompt shows the user entering ">> convert". The output shows: "Processing Data please wait...", "Converting Quantized Values to Voltages...", "Conversion Complete", "Data Processing Complete", "Would You Like to Save These Results? (y/n): y", "Filename: Test1", "Date/Time: 6/9/09", and ">>". There is an "OVR" button in the bottom right corner.

```
>> convert
Processing Data please wait...
Converting Quantized Values to Voltages...
Conversion Complete
Data Processing Complete
Would You Like to Save These Results? (y/n): y
Filename: Test1
Date/Time: 6/9/09
>>
```

FIGURE 7.2 - CONVERT.M COMMAND WINDOW OUTPUT

A screenshot of a Notepad window titled "Test1 - Notepad". The menu bar includes "File", "Edit", "Format", "View", and "Help". The text content is: "Filename: Test1", "DATE: 6/9/09", "---Data Received from optical sensor---", followed by a list of voltage readings: 0.58594, 0.60547, 0.58594, 0.52734, 3.5742, 3.5547, 3.5938, 3.5547, 3.5742, and 3.5547.

```
Filename: Test1
DATE: 6/9/09
---Data Received from optical sensor---
0.58594
0.60547
0.58594
0.52734
3.5742
3.5547
3.5938
3.5547
3.5742
3.5547
```

FIGURE 7.3 - VOLTAGES SAVED TO THE TEXT FILE

In Figure 7.3, the sensor is initially covered and then exposed to ambient light. When covered, the voltage readings are below 1 V and reach approximately 3.5 V in the ambient light. After the data are collected using connect.m and saved to a text file, convert.m generates a plot to graphically show the data gathered by the sensor. In Figure 7.4, the data for a test run with the sensor open to ambient light is plotted for each ADC conversion.

FIGURE 7.4 - VOLTAGE PLOT WITH AMBIENT LIGHT

7.1.3 Compare.m

Once multiple data captures have been converted and saved to a file, they can then be compared (up to three data sets). Each of the different sets of voltages is plotted on the same graph to show the differences or similarities between them. This is useful for gathering a few sets of data for the same type of test to check for consistency in the method of testing or to compare healthy data vs. unhealthy data. In Figure 7.5 shown below, three different tests have been performed and plotted against each other. Test 1 shows the voltages output from the sensor in ambient light, Test 2 shows the voltages output from the sensor when light is partially restricted but held constant, and Test 3 shows a random set of voltages generated by varying the sensor input in an arbitrary manner.

FIGURE 7.5 - COMPARE.M COMPARISON PLOT FOR 3 DIFFERENT TEST RUNS

Although the tests for this section have been performed using 512 bytes of data, the number of bytes can be specified to collect data for longer periods of time. Any 2^n number of bytes can be specified to offer longer periods of data collection or more accurate comparisons can be performed over time.

7.2 Real-Time Data Plotting

Using the three MATLAB™ files described above is useful when small amounts of data need to be collected or compared. However, when data must be collected over extended periods of time or a clinician wishes to view data from the sensor as it is collected, the real-time data capture software then becomes quite useful. For this software, a graphical user interface (GUI) was created in MATLAB™. The GUI allows for data capture to be started and viewed in real-time, without needing to explicitly run any MATLAB™ files. The real-time data plotting software works in two separate steps. First, once “Start” is

clicked on the GUI, the software will initially capture 25 data points in real-time. After 25 data points, the software shifts the x-axis of the plot and adds one new point while removing the previous point (each 25 samples apart). This allows the plot to move with the number of samples taken over time and provides a current look at what voltages the sensor is producing at any given time. A sample is taken from the incoming wireless data every 0.5 seconds, so the x-axis is labeled in seconds, with two samples being taken each second. Sampling once per second was too slow when looking at the plot and anymore than two samples per second became redundant. Therefore, two samples were chosen per second to represent the gathered data; however, data could be averaged over time and plotted rather than sampling the incoming data. Displayed below in Figure 7.6 is an example of the real-time data plot GUI.

FIGURE 7.6 - REAL-TIME VOLTAGE PLOT

CHAPTER VIII

FUTURE WORK

Although much has been accomplished on the wireless system integration and the NIR optical sensor, there are still many tasks that need to be completed. As mentioned in Section 3.2.3, a main future goal is to develop a multichannel sensing array that can record data over a larger area or in several different areas simultaneously. This will require updating the control and data processing circuitry to handle multiple data signals. It will also require more processing power to perform all of the voltage quantization that right now, only one ADC is handling. The ADC can handle multiple conversions, but to do so, the circuitry will have to be reconfigured to trigger each of the different conversions.

A portable power system will also need to be developed in order to allow the entire system to migrate away from the current power source that has been used over the course of the systems development. This will require some engineering of a battery pack that will easily power the system and not inhibit use. Size and weight will be factors in the development of this powering system as well as the amount of power that will be required for different types of testing (i.e. number of sensors, accuracy of data conversion, etc.)

Another future focus will be to research ways to increase system functionality by implementing on-board digital signal processing methods. Data averaging could be used to remove some of the load that is currently being taken on by the MATLAB™ portion of

the system. Also, moving the data conversion to the board could increase the overall speed of data collection.

The phantom development is also in its early stages, and will need to be thoroughly researched in order to create more sophisticated testing applications. Currently, the titanium dioxide and carbon black tests have served as a preliminary testing base to prove the functionality of the system. However, in the future these phantoms must be refined to provide more accurate sensor testing.

Finally, once the fNIRS system has been completed, the entire system will be moved to a FPGA. This will allow for all of the circuitry to be moved to one chip, add versatility to the fNIRS wireless system, and greatly increase the number of applications that it could be used for.

REFERENCES

- [1] M. D. ,. K. Gross. (2006, Sep.) U.S. National Library of Medicine and National Institutes of Health. [Online]. <http://www.nlm.nih.gov/medlineplus/ency/article/003931.htm>
- [2] O. I. Tanzer, "Numerical Modeling in Electro- And Magnetoencephalography," PhD Thesis, Helsinki University of Technology, Espoo, Finland, 2006.
- [3] G. K. Bergey and P. J. Franaszczuk, "Epileptic Seizures are Characterized by Changing Signal Complexity," Johns Hopkins University School of Medicine Technical Paper, 2000.
- [4] M. Hamalainen. (2004, Dec.) Athinoula A. Martinos Center for Biomedical Imaging. [Online]. <http://www.nmr.mgh.harvard.edu/martinos/research/technologiesMEG.php>
- [5] D. A. Boas, et al., "Imaging the Body with Diffuse Optical Tomography," *IEEE Signal Processing Magazine*, vol. 18, no. 6, pp. 57-75, Nov. 2001.
- [6] L. Wald. (2005, Feb.) Athinoula A. Martinos Center for Biomedical Imaging. [Online]. <http://www.nmr.mgh.harvard.edu/martinos/research/technologiesMR.php>
- [7] N. Savage, "A Weaker, Cheaper MRI," *IEEE Spectrum Online*, Jan. 2008.
- [8] B. W. Murphy. (2005, Sep.) Center for Positron Emission Tomography (CPET): University of Buffalo. [Online]. <http://www.nucmed.buffalo.edu/prevweb/petdef.htm>
- [9] J. M. Ollinger and J. A. Fessler, "Positron Emission Tomography," *IEEE Signal Processing Magazine*, vol. 14, no. 1, pp. 43-55, Jan. 1997.
- [10] University of Virginia. (2007, Dec.) University of Virginia Health System. [Online]. http://www.healthsystem.virginia.edu/uvahealth/adult_radiology/pet.cfm
- [11] A. Assmus, "Early History of X Rays," *Beam Line*, vol. 25, no. 2, pp. 10-24, 1995.
- [12] M. Wolf and M. F. V. Quaresima, "Progress of near-infrared spectroscopy and topography for brain and muscle clinical applications," *Journal of Biomedical Optics*, vol. 12, no. 6, Dec. 2007.
- [13] D. T. Delpy, M. Ferrari, C. A. Piantadosi, and M. Tamura, "Pioneers in Biomedical Optics: Special Section Honoring Professor Frans F. Jobsis of Duke University," *Journal of Biomedical Optics*, vol. 12, no. 6, Dec. 2007.
- [14] V. A. Markel and J. C. Schotland, "Single-Scattering Optical Tomography," in *Conference on Lasers and Electro-Optics*, Baltimore, MD, 2007, pp. 1-2.

- [15] A. P. Gibson, J. C. Hebden, and S. R. Arridge, "Recent advances in diffuse optical imaging," *Physics in Medicine and Biology*, vol. 50, no. 4, pp. R1-R43, Feb. 2005.
- [16] M. Izzetoglu, S. C. Bunce, K. Izzetoglu, B. Onaral, and K. Pourrezaei, "Functional Brain Imaging Using Near-Infrared Technology," *IEEE Engineering In Medicine and Biology Magazine*, vol. 26, no. 4, pp. 38-46, Aug. 2007.
- [17] G. Strangman, D. A. Boas, and J. P. Sutton, "Non-Invasive Neuroimaging Using Near-Infrared Light," *Society of Biological Psychiatry*, vol. 52, no. 7, pp. 679-693, Oct. 2002.
- [18] A. Bozkurt, A. Rosen, H. Rosen, and B. Onaral, "A portable near infrared spectroscopy system for bedside monitoring of newborn brain," *BioMedical Engineering OnLine*, Apr. 2005.
- [19] A. Villringer and B. Chance, "Non-invasive optical spectroscopy and imaging of human brain function," *Trends in Neurosciences*, vol. 20, no. 10, pp. 435-442, Oct. 1997.
- [20] M. Schweiger, A. Gibson, and S. R. Arridge, "Computational Aspects of Diffuse Optical Tomography," *Computing in Science and Engineering*, vol. 5, no. 6, pp. 33-41, Nov. 2003.
- [21] B. N. Pasley and R. D. Freeman. (2008, May) Neurovascular Coupling. Article.
- [22] S. C. Bunce, M. Izzetoglu, K. Izzetoglu, B. Onaral, and K. Pourrezaei, "Functional Near-Infrared Spectroscopy: An Emerging Neuroimaging Modality," *IEEE Engineering in Medicine and Biology Magazine*, vol. 25, no. 4, pp. 54-62, Jul. 2007.
- [23] P. Rolfe, "In Vivo Near-Infrared Spectroscopy," *Annu. Rev. Biomed. Eng.*, vol. 2, pp. 715-754, 2000.
- [24] Duncan Seddon & Associates. (2003, Jan.) Resin Portrait ABS. Document.
- [25] Radicom Research, Inc. (2007) Radicom. [Online].
<http://www.radi.com/modular43.htm>
- [26] D. A. Boas, M. A. Franceschini, A. K. Dunn, and G. Strangman, "Noninvasive Imaging of Cerebral Activation with Diffuse Optical Tomography," in *In Vivo Optical Imaging of Brain Function*, R. D. Frostig, Ed. Boca Raton: CRC Press, 2002, ch. 8, pp. 193-221.
- [27] A. G. Webb, "X-Ray Imaging and Computed Tomography," in *Introduction to Biomedical Imaging*, 2002, ch. 1, pp. 1-55.
- [28] R. Nave. (2006) HyperPhysics - Georgia State Univeristy. [Online].
<http://hyperphysics.phy-astr.gsu.edu/Hbase/atmos/blusky.html>

APPENDIX A – Epitex LED Spec Sheet

epitex

Opto-Device & Custom LED $\Phi 8$ STEM TYPE LED L4*730/4*805/4*850-40Q96-I

Lead (Pb) Free Product RoHS compliant

L4*730/4*805/4*850-40Q96-I multi-wavelength LED

◆Outer dimension (Unit: mm)

L4*730/4*805/4*850-40Q96-I consists of 12chips of AlGaAs (730nm, 805nm and 850nm) LED mounted with AlN heat sink pedestal on TO-5 stem and sealed with a flat glass can.

◆Specifications

- 1) Product Name multi-wavelength LED
- 2) Type No. L4*730/4*805/4*850-40Q96-I
- 3) Chip
 - (1) Chip material AlGaAs
 - (2) Peak wavelength 730, 805, 850nm
 - (3) Chip numbers Each 4pcs
- 4) Package
 - (1) Stem TO-5, 8pin type
 - (2) Lens Flat glass can

◆Absolute Maximum Ratings [Ta=25°C]

Item	Symbol	Maximum Rated Value			Unit
		730	805	850	
Power Dissipation	P _D	720	680	640	mW
Forward Current	I _F	75	100	100	mA
Pulse Forward Current	I _F	200	300	500	mA
Reverse Voltage	V _R	5			V
Operating Temperature	T _{OPR}	-20 ~ +80			°C
Storage Temperature	T _{STG}	-30 ~ +100			°C
Soldering Temperature	T _{SOL}	240			°C

‡Soldering condition: Soldering condition must be completed within 3 seconds at 240°C and is allowed in the area apart 3mm from the bottom of the lamp.

◆Electro-Optical Characteristics [Ta=25°C]

Symbol	Wavelength	Condition	Minimum	Typical	Maximum	Unit
V _F	730	I _F =50mA		7.6	9.0	V
	805			6.4	7.2	
	850			5.6	6.5	
I _R	730	V _R =10V	15	30	10	uA
	805		18	30		
	850		20	30		
P _O	730	I _F =50mA				mW
	805					
	850					
λ _P	730	I _F =50mA	715	730	745	nm
	805		790	805	820	
	850		835	850	865	
Δλ	730	I _F =50mA		30		nm
	805			40		
	850			40		

‡Total Radiated Power is measured by Photodyne#500

EPITEX INC. : 4, Nishiaketa-Cho, Higashi-Kujyou, Minami-Ku, Kyoto, Japan

Tel.: ++81-75-682-2338 Fax: ++81-75-682-2267

e-mail: sales-dep@epitex.com <http://www.epitex.com>

APPENDIX B – OPT101 Photodiode Spec Sheet

OPT101

MONOLITHIC PHOTODIODE AND SINGLE-SUPPLY TRANSIMPEDANCE AMPLIFIER

FEATURES

- SINGLE SUPPLY: +2.7 to +36V
- PHOTODIODE SIZE: 0.090 x 0.090 inch
- INTERNAL 1M Ω FEEDBACK RESISTOR
- HIGH RESPONSIVITY: 0.45A/W (650nm)
- BANDWIDTH: 14kHz at R_F = 1M Ω
- LOW QUIESCENT CURRENT: 120 μ A
- AVAILABLE IN 8-PIN DIP, 5-PIN SIP, AND 8-LEAD SURFACE MOUNT PACKAGES

APPLICATIONS

- MEDICAL INSTRUMENTATION
- LABORATORY INSTRUMENTATION
- POSITION AND PROXIMITY SENSORS
- PHOTOGRAPHIC ANALYZERS
- BARCODE SCANNERS
- SMOKE DETECTORS
- CURRENCY CHANGERS

DESCRIPTION

The OPT101 is a monolithic photodiode with on-chip transimpedance amplifier. Output voltage increases linearly with light intensity. The amplifier is designed for single or dual power supply operation, making it ideal for battery operated equipment.

The integrated combination of photodiode and transimpedance amplifier on a single chip eliminates the problems commonly encountered in discrete designs such as leakage current errors, noise pick-up and gain peaking due to stray capacitance. The 0.09 x 0.09 inch photodiode is operated in the photoconductive mode for excellent linearity and low dark current.

The OPT101 operates from +2.7V to +36V supplies and quiescent current is only 120 μ A. It is available in clear plastic 8-pin DIP, 5-pin SIP and J-formed DIP for surface mounting. Temperature range is 0°C to 70°C.

PIN CONFIGURATIONS

ABSOLUTE MAXIMUM RATINGS

Supply Voltage (V_s to "Common" or pin 3)	0 to +36V
Output Short-Circuit (to ground)	Continuous
Operating Temperature	-25°C to +85°C
Storage Temperature	-25°C to +85°C
Junction Temperature	+85°C
Lead Temperature (soldering, 10s)	+300°C
(Vapor-Phase Soldering Not Recommended)	

PACKAGE INFORMATION

PRODUCT	COLOR	PACKAGE	PACKAGE DRAWING NUMBER ⁽¹⁾
OPT101P	Clear	8-Pin Plastic DIP	006-1
OPT101P-J	Clear	8-Lead Surface Mount ⁽²⁾	006-4
OPT101W	Clear	5-Pin Plastic SIP	321

NOTE: (1) For detailed drawing and dimension table, please see end of data sheet, or Appendix C of Burr-Brown IC Data Book. (2) 8-pin DIP with J-formed leads for surface mounting.

ELECTROSTATIC DISCHARGE SENSITIVITY

This integrated circuit can be damaged by ESD. Burr-Brown recommends that all integrated circuits be handled with appropriate precautions. Failure to observe proper handling and installation procedures can cause damage.

ESD damage can range from subtle performance degradation to complete device failure. Precision integrated circuits may be more susceptible to damage because very small parametric changes could cause the device not to meet its published specifications.

MOISTURE SENSITIVITY AND SOLDERING

Clear plastic does not contain the structural-enhancing fillers used in black plastic molding compound. As a result, clear plastic is more sensitive to environmental stress than black plastic. This can cause difficulties if devices have been stored in high humidity prior to soldering. The rapid heating during soldering can stress wire bonds and cause failures. Prior to soldering, it is recommended that plastic devices be baked-out at +85°C for 24 hours.

The fire-retardant fillers used in black plastic are not compatible with clear molding compound. The OPT101 plastic packages cannot meet flammability test, UL-94.

APPENDIX C – Variable Gain Amplifier Spec Sheet

Dual Low Power Operational Amplifiers

Utilizing the circuit designs perfected for recently introduced Quad Operational Amplifiers, these dual operational amplifiers feature 1) low power drain, 2) a common mode input voltage range extending to ground/VEE, 3) single supply or split supply operation and 4) pinouts compatible with the popular MC1558 dual operational amplifier. The LM158 series is equivalent to one-half of an LM124.

These amplifiers have several distinct advantages over standard operational amplifier types in single supply applications. They can operate at supply voltages as low as 3.0 V or as high as 32 V, with quiescent currents about one-fifth of those associated with the MC1741 (on a per amplifier basis). The common mode input range includes the negative supply, thereby eliminating the necessity for external biasing components in many applications. The output voltage range also includes the negative power supply voltage.

- Short Circuit Protected Outputs
- True Differential Input Stage
- Single Supply Operation: 3.0 V to 32 V
- Low Input Bias Currents
- Internally Compensated
- Common Mode Range Extends to Negative Supply
- Single and Split Supply Operation
- Similar Performance to the Popular MC1558
- ESD Clamps on the Inputs Increase Ruggedness of the Device without Affecting Operation

MAXIMUM RATINGS ($T_A = +25^\circ\text{C}$, unless otherwise noted.)

Rating	Symbol	LM258 LM358	LM2904 LM2904V	Unit
Power Supply Voltages Single Supply Split Supplies	V_{CC} V_{CC}, V_{EE}	32 ±16	26 ±13	Vdc
Input Differential Voltage Range (Note 1)	V_{IDH}	+32	+26	Vdc
Input Common Mode Voltage Range (Note 2)	V_{ICM}	-0.3 to 32	-0.3 to 26	Vdc
Output Short Circuit Duration	t_{SC}	Continuous		
Junction Temperature	T_J	150		$^\circ\text{C}$
Storage Temperature Range	T_{stg}	-55 to +125		$^\circ\text{C}$
Operating Ambient Temperature Range	T_A			$^\circ\text{C}$
LM258		-25 to +85	-	
LM358		0 to +70	-	
LM2904		-	-40 to +105	
LM2904V		-	-40 to +125	

NOTES: 1. Split Power Supplies

2. For Supply Voltages less than 32 V for the LM258/358 and 26 V for the LM2904, the absolute maximum input voltage is equal to the supply voltage.

LM358, LM258, LM2904, LM2904V

DUAL DIFFERENTIAL INPUT OPERATIONAL AMPLIFIERS

SEMICONDUCTOR TECHNICAL DATA

N SUFFIX
PLASTIC PACKAGE
CASE 626

D SUFFIX
PLASTIC PACKAGE
CASE 751
(SO-8)

PIN CONNECTIONS

ORDERING INFORMATION

Device	Operating Temperature Range	Package
LM2904D	$T_A = -40^\circ$ to $+105^\circ\text{C}$	SO-8
LM2904N		Plastic DIP
LM2904VD	$T_A = -40^\circ$ to $+125^\circ\text{C}$	SO-8
LM2904VN		Plastic DIP
LM258D	$T_A = -25^\circ$ to $+85^\circ\text{C}$	SO-8
LM258N		Plastic DIP
LM358D	$T_A = 0^\circ$ to $+70^\circ\text{C}$	SO-8
LM358N		Plastic DIP

© Motorola, Inc. 1996

Rev 2

APPENDIX D – Analog to Digital Converter Spec Sheet

TLC0831C, TLC0831I TLC0832C, TLC0832I 8-BIT ANALOG-TO-DIGITAL CONVERTERS WITH SERIAL CONTROL

SLAS107B – JANUARY 1995 – REVISED APRIL 1996

- 8-Bit Resolution
- Easy Microprocessor Interface or Standalone Operation
- Operates Ratiometrically or With 5-V Reference
- Single Channel or Multiplexed Twin Channels With Single-Ended or Differential Input Options
- Input Range 0 to 5 V With Single 5-V Supply
- Inputs and Outputs Are Compatible With TTL and MOS
- Conversion Time of 32 μ s at $f_{\text{clock}} = 250$ kHz
- Designed to Be Interchangeable With National Semiconductor ADC0831 and ADC0832
- Total Unadjusted Error $\dots \pm 1$ LSB

TLC0831 ... D OR P PACKAGE
(TOP VIEW)

TLC0832 ... D OR P PACKAGE
(TOP VIEW)

description

These devices are 8-bit successive-approximation analog-to-digital converters. The TLC0831 has single input channels; the TLC0832 has multiplexed twin input channels. The serial output is configured to interface with standard shift registers or microprocessors.

The TLC0832 multiplexer is software configured for single-ended or differential inputs. The differential analog voltage input allows for common-mode rejection or offset of the analog zero input voltage value. In addition, the voltage reference input can be adjusted to allow encoding any smaller analog voltage span to the full 8 bits of resolution.

The operation of the TLC0831 and TLC0832 devices is very similar to the more complex TLC0834 and TLC0838 devices. Ratiometric conversion can be attained by setting the REF input equal to the maximum analog input signal value, which gives the highest possible conversion resolution. Typically, REF is set equal to V_{CC} (done internally on the TLC0832).

The TLC0831C and TLC0832C are characterized for operation from 0°C to 70°C. The TLC0831I and TLC0832I are characterized for operation from -40°C to 85°C.

AVAILABLE OPTIONS

T _A	PACKAGE			
	SMALL OUTLINE (D)		PLASTIC DIP (P)	
0°C to 70°C	TLC0831CD	TLC0832CD	TLC0831CP	TLC0832CP
-40°C to 85°C	TLC0831ID	TLC0832ID	TLC0831IP	TLC0832IP

TLC0831C, TLC0831I
TLC0832C, TLC0832I
8-BIT ANALOG-TO-DIGITAL CONVERTERS WITH SERIAL CONTROL
SLAS107I – JANUARY 1995 – REVISED APRIL 1995

sequence of operation

TLC0832 MUX-ADDRESS CONTROL LOGIC TABLE

MUX ADDRESS		CHANNEL NUMBER	
SGL/DIF	ODD/EVEN	CH0	CH1
L	L	--	--
L	H	--	--
H	L	1	1
H	H	1	1

H = high level, L = low level,
 -- or -- = terminal output for the selected input channel

APPENDIX E – Counter Spec Sheet

Philips Semiconductors

Product specification

Presetable synchronous 4-bit binary
counter; asynchronous reset

74HC/HCT161

ORDERING INFORMATION

See "74HC/HCT/HCU/HCMOS Logic Package Information".

PIN DESCRIPTION

PIN NO.	SYMBOL	NAME AND FUNCTION
1	$\overline{MR}$	asynchronous master reset (active LOW)
2	CP	clock input (LOW-to-HIGH, edge-triggered)
3, 4, 5, 6	D_0 to D_3	data inputs
7	CEP	count enable input
8	GND	ground (0 V)
9	$\overline{PE}$	parallel enable input (active LOW)
10	CET	count enable carry input
14, 13, 12, 11	Q_0 to Q_3	flip-flop outputs
15	TC	terminal count output
16	V_{CC}	positive supply voltage

Presettable synchronous 4-bit binary counter; asynchronous reset

74HC/HCT161

Fig.5 State diagram.

Fig.6 Typical timing sequence: reset outputs to zero; preset to binary twelve; count to thirteen, fourteen, fifteen, zero, one and two; inhibit.

APPENDIX F – NAND Gate Spec Sheet

SN54HC20, SN74HC20 DUAL 4-INPUT POSITIVE-NAND GATES

SCL5056F – DECEMBER 1982 – REVISED AUGUST 2003

- Wide Operating Voltage Range of 2 V to 6 V
- Outputs Can Drive Up To 10 LSTTL Loads
- Low Power Consumption, 20- μ A Max I_{CC}
- Typical $t_{pd} = 11$ ns
- ± 4 -mA Output Drive at 5 V
- Low Input Current of 1 μ A Max

SN54HC20 . . . J OR W PACKAGE
SN74HC20 . . . D, DB, N, NS, OR PW PACKAGE
(TOP VIEW)

SN54HC20 . . . FK PACKAGE
(TOP VIEW)

NC No internal connection

description/ordering information

The 'HC20 devices contain two independent 4-input NAND gates. They perform the Boolean function $Y = \overline{A \cdot B \cdot C \cdot D}$ or $Y = \overline{A + B + C + D}$ in positive logic.

ORDERING INFORMATION

T_A	PACKAGE†		ORDERABLE PART NUMBER	TOP-SIDE MARKING
-40°C to 85°C	PDIP – N	Tube of 25	SN74HC20N	HC20
		Tube of 50	SN74HC20D	
	SOIC – D	Reel of 2500	SN74HC20DR	HC20
		Reel of 250	SN74HC20D1	
	SOIC – NS	Reel of 2000	SN74HC20NSR	HC20
	SSOP – DB	Reel of 2000	SN74HC20DBR	HC20
55°C to 125°C	TSSOP – PW	Tube of 90	SN74HC20PW	HC20
		Reel of 2000	SN74HC20PWR	
		Reel of 250	SN74HC20PW1	
	CDIP – J	Tube of 25	SNJ54HC20J	SNJ54HC20J
	CDIP – W	Tube of 100	SNJ54HC20W	SNJ54HC20W
	LCOC – FK	Tube of 55	SNJ54HC20FK	SNJ54HC20FK

† Package drawings, standard packing quantities, thermal data, symbolization, and PCB design guidelines are available at www.ti.com/sc/package

APPENDIX G – Inverter Spec Sheet

MC14049UB

Hex Buffers

The MC14049UB hex inverter/buffer is constructed with MOS P-channel and N-channel enhancement mode devices in a single monolithic structure. This complementary MOS device finds primary use where low power dissipation and/or high noise immunity is desired. This device provides logic-level conversion using only one supply voltage, V_{DD} . The input-signal high level (V_{IH}) can exceed the V_{DD} supply voltage for logic-level conversions. Two TTL/DTL Loads can be driven when the device is used as CMOS-to-TTL/DTL converters ($V_{DD} = 5.0\text{ V}$, $V_{OL} \leq 0.4\text{ V}$, $I_{OL} \geq 3.2\text{ mA}$). Note that pins 13 and 16 are not connected internally on this device; consequently connections to these terminals will not affect circuit operation.

- High Source and Sink Currents
- High-to-Low Level Converter
- Supply Voltage Range = 3.0 V to 18 V
- Meets JEDEC UB Specifications
- V_{IN} can exceed V_{DD}
- Improved ESD Protection on All Inputs

MAXIMUM RATINGS (Voltages Referenced to V_{SS}) (Note 2.)

Symbol	Parameter	Value	Unit
V_{DD}	DC Supply Voltage Range	-0.5 to +18.0	V
V_{in}	Input Voltage Range (DC or Transient)	-0.5 to +18.0	V
V_{out}	Output Voltage Range (DC or Transient)	-0.5 to $V_{DD} + 0.5$	V
I_{in}	Input Current (DC or Transient) per Pin	± 10	mA
I_{out}	Output Current (DC or Transient) per Pin	± 45	mA
P_D	Power Dissipation, per Package (Note 3.) Plastic SOIC	825 740	mW
T_A	Ambient Temperature Range	-55 to +125	°C
T_{stg}	Storage Temperature Range	-65 to +150	°C
T_L	Lead Temperature (8-Second Soldering)	260	°C

- Maximum Ratings are those values beyond which damage to the device may occur.
- Temperature Derating:
All Packages: See Figure 4.

This device contains circuitry to protect the inputs against damage due to high static voltages or electric fields referenced to the V_{SS} pin, only. Extra precautions must be taken to avoid applications of any voltage higher than the maximum rated voltages to this high-impedance circuit. For proper operation, the ranges $V_{SS} \leq V_{in} \leq 18\text{ V}$ and $V_{SS} \leq V_{out} \leq V_{DD}$ are recommended.

Unused inputs must always be tied to an appropriate logic voltage level (e.g., either V_{SS} or V_{DD}). Unused outputs must be left open.

ON Semiconductor

<http://onsemi.com>

MARKING DIAGRAMS

PDIP-16
P SUFFIX
CASE 648

SOIC-16
D SUFFIX
CASE 751B

TSSOP-16
DT SUFFIX
CASE 948F

SOEIAJ-16
F SUFFIX
CASE 966

A = Assembly Location
WL or L = Wafer Lot
YY or Y = Year
WW or W = Work Week

ORDERING INFORMATION

Device	Package	Shipping
MC14049UBCP	PDIP-16	2000/Box
MC14049UBD	SOIC-16	2400/Box
MC14049UBDR2	SOIC-16	2500/Tape & Reel
MC14049UBDT	TSSOP-16	96/Rail
MC14049UBDTR2	TSSOP-16	2500/Tape & Reel
MC14049UBF	SOEIAJ-16	See Note 1.
MC14049UBFEL	SOEIAJ-16	See Note 1.

- For ordering information on the EIAJ version of the SOIC packages, please contact your local ON Semiconductor representative.

MC14049UB

LOGIC DIAGRAM MC14049UB

NC = PIN 13, 16
V_{SS} = PIN 8
V_{DD} = PIN 1

CIRCUIT SCHEMATIC (1/6 OF CIRCUIT SHOWN)

APPENDIX H – Flip-Flop Spec Sheet

Dual D Flip-Flop with Set and Reset

High-Performance Silicon-Gate CMOS

The MC54/74HC74A is identical in pinout to the LS74. The device inputs are compatible with standard CMOS outputs; with pullup resistors, they are compatible with LSTTL outputs.

This device consists of two D flip-flops with individual Set, Reset, and Clock inputs. Information at a D-input is transferred to the corresponding Q output on the next positive going edge of the clock input. Both Q and $\bar{Q}$ outputs are available from each flip-flop. The Set and Reset inputs are asynchronous.

- Output Drive Capability: 10 LSTTL Loads
- Outputs Directly Interface to CMOS, NMOS, and TTL
- Operating Voltage Range: 2.0 to 6.0 V
- Low Input Current: 1.0 μ A
- High Noise Immunity Characteristic of CMOS Devices
- In Compliance with the Requirements Defined by JEDEC Standard No. 7A
- Chip Complexity: 128 FETs or 32 Equivalent Gates

LOGIC DIAGRAM

MC54/74HC74A

J SUFFIX
CERAMIC PACKAGE
CASE 632-08

N SUFFIX
PLASTIC PACKAGE
CASE 646-06

D SUFFIX
SOIC PACKAGE
CASE 751A-03

DT SUFFIX
TSSOP PACKAGE
CASE 940G-01

ORDERING INFORMATION

MC54HC74AJ	Ceramic
MC74HC74AN	Plastic
MC74HC74AD	SOIC
MC74HC74ADT	TSSOP

PIN ASSIGNMENT

RESET 1	1	14	VCC
DATA 1	2	13	RESET 2
CLOCK 1	3	12	DATA 2
SET 1	4	11	CLOCK 2
Q1	5	10	SET 2
Q1	6	9	Q2
GND	7	8	Q2

FUNCTION TABLE

Inputs				Outputs	
Set	Reset	Clock	Data	Q	Q
L	H	X	X	H	L
H	L	X	X	L	H
L	L	X	X	H*	H*
H	H	✓	H	H	L
H	H	✓	L	L	H
H	H	L	X	No Change	No Change
H	H	H	X	No Change	No Change
H	H	✓	X	No Change	No Change

* Both outputs will remain high as long as Set and Reset are low, but the output states are unpredictable if Set and Reset go high simultaneously.

APPENDIX I – On-Board Clock Spec Sheet

February 2000

LM555 Timer

LM555 Timer

General Description

The LM555 is a highly stable device for generating accurate time delays or oscillation. Additional terminals are provided for triggering or resetting if desired. In the time delay mode of operation, the time is precisely controlled by one external resistor and capacitor. For astable operation as an oscillator, the free running frequency and duty cycle are accurately controlled with two external resistors and one capacitor. The circuit may be triggered and reset on falling waveforms, and the output circuit can source or sink up to 200mA or drive TTL circuits.

Features

- Direct replacement for SE555/NE555
- Timing from microseconds through hours
- Operates in both astable and monostable modes
- Adjustable duty cycle
- Output can source or sink 200 mA
- Output and supply TTL compatible
- Temperature stability better than 0.005% per °C
- Normally on and normally off output
- Available in 8-pin MSOP package

Applications

- Precision timing
- Pulse generation
- Sequential timing
- Time delay generation
- Pulse width modulation
- Pulse position modulation
- Linear ramp generator

Connection Diagram

Ordering Information

Package	Part Number	Package Marking	Media Transport	NSC Drawing
8-Pin SOIC	LM555CM	LM555CM	Reels	M08A
	LM555CMX	LM555CM	2.5k Units Tape and Reel	
8-Pin MSOP	LM555CMM	Z55	1k Units Tape and Reel	MUA08A
	LM555CMMX	Z55	3.5k Units Tape and Reel	
8-Pin PDIP	LM555CN	LM555CN	Reels	N08F

Applications Information (Continued)

50% DUTY CYCLE OSCILLATOR

For a 50% duty cycle, the resistors R_A and R_B may be connected as in Figure 14. The time period for the output high is the same as previous, $t_1 = 0.693 R_A C$. For the output low it is $t_2 =$

$$\left[(R_A R_B) / (R_A - R_B) \right] C \ln \left[\frac{R_B - 2R_A}{2R_B - R_A} \right]$$

Thus the frequency of oscillation is

$$f = \frac{1}{t_1 + t_2}$$

DS90C07-1.13

FIGURE 14. 50% Duty Cycle Oscillator

Note that this circuit will not oscillate if R_B is greater than $1/2 R_A$ because the junction of R_A and R_B cannot bring pin 2 down to $1/3 V_{CC}$ and trigger the lower comparator.

ADDITIONAL INFORMATION

Adequate power supply bypassing is necessary to protect associated circuitry. Minimum recommended is $0.1\mu F$ in parallel with $1\mu F$ electrolytic.

Lower comparator storage time can be as long as $10\mu s$ when pin 2 is driven fully to ground for triggering. This limits the monostable pulse width to $10\mu s$ minimum.

Delay time reset to output is $0.47\mu s$ typical. Minimum reset pulse width must be $0.3\mu s$, typical.

Pin 7 current switches within $30ns$ of the output (pin 3) voltage.

APPENDIX J – MATLAB™ Code

Connect.m

```
%This function controls all of the processes required for opening and  
%connecting to the serial port. It also reads a user defined amount of  
%bytes from the serial port, and forwards that data to the Wireless  
%Data Conversion function.
```

```
clear all; close all; clc
```

```
%Query User for # of Bytes to Read  
numbytes = input('Enter the Number of Bytes to Read: ');
```

```
%Construct serial port object  
serialport = serial('COM1', 'BaudRate', 2400, 'FlowControl',...  
    'hardware', 'InputBufferSize', numbytes);
```

```
    display('Serial Port Connection Established')
```

```
%Connect the serial port object to the serial port  
fopen(serialport)  
display('Serial Port Open for Reading')
```

```
%Prompt user to begin data collection  
begin = input('Press 1 to Begin Reading or 2 to Quit: ','s');
```

```
if begin == '1';  
    %Read User Defined # of Bytes from Serial Port  
    dataread = fread(serialport,numbytes,'uint8');  
    display('Reading data please wait...')  
else  
    display('Read Cancelled')  
    return  
end
```

```
display('Data Read Complete')
```

```
%Disconnect the serial port object from the serial port  
fclose(serialport);
```

```
display('Serial Port Connection Closed')
```

```
%----- END of SERIAL PORT COMMUNICATION -----
```

Convert.m

```
%This function converts decimal numbers to binary strings. It then  
%reverses the binary strings and re-outputs them as decimal numbers.  
%It is used to reverse received data from the wireless board.
```

```
x = dataread';  
display('Processing Data please wait...')  
  
%Reverse All Received Data from Optical Sensor  
for i=1:length(x)  
  
    %Convert Decimal Values to Binary  
    binary = dec2bin(x(i), 8);  
  
    %Reverse Binary Values and Convert Back to Decimal  
    reversed(i,:) = bin2dec(binary(8:-1:1));  
  
end  
  
%Convert Quantized 0-255 Values to 0-5v Voltages  
voltages = (reversed*(5/256));  
  
grid on, hold on %Turn on grid and hold plots  
  
%Provide +1v Marker Lines (Red)  
plot([0,length(x)],[1,1],'--r','linewidth',1)  
plot([0,length(x)],[2,2],'--r','linewidth',1)  
plot([0,length(x)],[3,3],'--r','linewidth',1)  
plot([0,length(x)],[4,4],'--r','linewidth',1)  
plot([0,length(x)],[5,5],'--r','linewidth',1)  
  
%Plot Voltages Received from Optical Sensor  
plot(1:length(x),voltages, 'b', 'linewidth',2);  
title('Voltage Readings from Optical Sensor');  
xlabel('Sample #')  
ylabel(' Voltage Readings [0-5v]')  
  
display('Data Processing Complete')  
  
% Save the Optical Sensor Readings  
store = input('Would You Like to Save These Results? (y/n): ','s');  
  
%Prompt User for Filename If They Want To Save  
if store == 'y'  
    name = input('Filename: ','s');  
    date = input('Date/Time: ','s');  
else  
    close all;  
    return;  
end  
  
save_as = [name, '.txt']; %Filename  
fid = fopen(save_as,'wt'); %OPEN FILE TO WRITE TO  
  
if (fid < 0)
```



```

        error(['Could not open file ' save_as]);
end;

%WRITE IMAGE NAME AND DATE TO FILE
fprintf(fid,['Filename: ', name, '\n']);
fprintf(fid,['DATE: ', date, '\n']);
fprintf(fid,['---Data Received from Optical Sensor---\n']);

%Write voltages to text file
for j = 1:length(x)
    fprintf(fid,['', num2str(voltages(j,1)), '\n']);
end

%CLOSE FILE
fclose(fid);

%Save .mat File with the voltages
save(name, 'voltages')

%----- END of DATA PROCESSING -----

```

Compare.m

```
%This function allows the user to compare up to 3 different sets of  
%voltages for comparison.
```

```
%Prompt User to Compare Different Voltage Datasets
```

```
comparison = input('Would you like to comparison different datasets?  
y/n: ', 's');
```

```
%If User Chooses Yes, Run Comparison Code Otherwise Exit the Program
```

```
if comparison=='y';  
    num = input('Please enter the # of Samples to comparison (1-3):  
                ', 's');
```

```
else  
    display('Program Has Completed');  
    return;  
end
```

```
%Set Loop Max from User Selection
```

```
if num=='1'  
    max=1;  
elseif num=='2'  
    max=2;  
elseif num=='3'  
    max=3;  
end
```

```
%Define dataset names as empty strings
```

```
dataset1 = '';  
dataset2 = '';  
dataset3 = '';
```

```
%Hide figure until all datasets are plotted
```

```
hf = figure;  
set(hf, 'visible', 'off');
```

```
%Get sample names and load them for plotting
```

```
for d = 1:max  
    if d==1  
        colorchange = 'b';  
        dataset = input('Type Name of Sample: ', 's');  
        dataset1 = [dataset, '.mat'];  
        load (dataset1, 'voltages');  
    elseif d==2  
        colorchange = 'g';  
        dataset = input('Type Name of Sample: ', 's');  
        dataset2 = [dataset, '.mat'];  
        load (dataset2, 'voltages');  
    elseif d==3  
        colorchange = 'k';  
        dataset = input('Type Name of Sample: ', 's');  
        dataset3 = [dataset, '.mat'];  
        load (dataset3, 'voltages');  
    end
```



```

%Plot current dataset
plot(1:length(voltages),voltages,colorchange,'linewidth',2);...
hold on, grid on

%Label Figure
title(['Voltage Datasets from ', num2str(max),' Optical Sensor
      Readings']);
xlabel('Sample #')
ylabel(' Voltage Readings [0-5v]')

end

%Determine the Legend Based on Number of Comparisons
if max == 1
    legend(dataset1);
elseif max == 2
    legend(dataset1,dataset2);
elseif max==3
    legend(dataset1,dataset2,dataset3)
end

%Plot Red-Dashed Voltage Separation Lines Last
plot([0,length(voltages)],[1,1],'--r','linewidth',1)
plot([0,length(voltages)],[2,2],'--r','linewidth',1)
plot([0,length(voltages)],[3,3],'--r','linewidth',1)
plot([0,length(voltages)],[4,4],'--r','linewidth',1)
plot([0,length(voltages)],[5,5],'--r','linewidth',1)

%Show Final Plot Figure
set(hf,'visible','on')

%----- END of VOLTAGE DATASET COMPARISONS -----

```

GUI.m

%This function reads from the serial port and plots voltages in real time.

```
function varargout = GUI(varargin)
% GUI M-file for GUI.fig
%     GUI, by itself, creates a new GUI or raises the existing
%     singleton*.
%
%     H = GUI returns the handle to a new GUI or the handle to
%     the existing singleton*.
%
%     GUI('CALLBACK',hObject,eventData,handles,...) calls the local
%     function named CALLBACK in GUI.M with the given input arguments.
%
%     GUI('Property','Value',...) creates a new GUI or raises the
%     existing singleton*. Starting from the left, property value
%     pairs are applied to the GUI before GUI_OpeningFunction gets
%     called. An unrecognized property name or invalid value makes
%     property application stop. All inputs are passed to
%     GUI_OpeningFcn via varargin. *See GUI Options on GUIDE's Tools
%     menu. Choose "GUI allows only one instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES
% Edit the above text to modify the response to help GUI
% Last Modified by GUIDE v2.5 29-Jan-2008 13:22:54
% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                  'gui_Singleton',   gui_Singleton, ...
                  'gui_OpeningFcn',   @GUI_OpeningFcn, ...
                  'gui_OutputFcn',    @GUI_OutputFcn, ...
                  'gui_LayoutFcn',    [] , ...
                  'gui_Callback',     []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT

% --- Executes just before GUI is made visible.
function GUI_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles     structure with handles and user data (see GUIDATA)
% varargin    command line arguments to GUI (see VARARGIN)
set(hObject,'toolbar','figure');
% Choose default command line output for GUI
handles.output = hObject;
```



```

% Update handles structure
guidata(hObject, handles);

% UIWAIT makes GUI wait for user response (see UIRESUME)
% uiwait(handles.figure1);

% --- Outputs from this function are returned to the command line.
function varargout = GUI_OutputFcn(hObject, eventdata, handles)
% varargout cell array for returning output args (see VARARGOUT);
% hObject handle to figure
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;

% --- Executes on button press in start.
function start_Callback(hObject, eventdata, handles)
% hObject handle to start (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

%selects axes1 as the current axes, so that
%Matlab knows where to plot the data

fclose(instrfind) %Close all open serial port connections

%Define serial port object
serialport = serial('COM1', 'BaudRate', 2400, 'FlowControl',...
                    'hardware','InputBufferSize',1);

%Open serial port
fopen(serialport)
axes(handles.axes3)
window = 25; %Define window size
i=0; %Initialize loop index

%Fill initial window with data points
for i = 1:window

    %Read and convert data from serial port
    dataread = fread(serialport,1,'uint8');
    x = dataread';
    binary = dec2bin(x, 8);
    reversed(i,:) = bin2dec(binary(8:-1:1));
    voltages = (reversed*(5/256));

    %Plot voltages in real time
    plot(i/2,voltages(i),'b*','linewidth',2);hold on;axis on;grid on

    %Adds a title, x-axis description, and y-axis description
    title('Voltage Readings from Optical Sensor');
    xlabel('Time');
    ylabel(' Voltage Readings [0-5v]')
    guidata(hObject, handles); %updates the handles
    pause(.5);
end

```

```

%Increment window and add new data point ever 0.5 seconds
for i = (window+1):600000

    %Read and convert data from serial port
    dataread = fread(serialport,1,'uint8');
    x = dataread';
    binary = dec2bin(x, 8);
    reversed(i,:) = bin2dec(binary(8:-1:1));
    voltages = (reversed*(5/256));

    %plot voltages in real time
    plot(i/2,voltages(i),'b*');
    axis([(i/2)-window, window+(i/2), 0, 5]);

    %Adds a title, x-axis description, and y-axis description
    title('Voltage Readings from Optical Sensor');
    xlabel('Time');
    ylabel(' Voltage Readings [0-5v]');
    guidata(hObject, handles); %updates the handles
    pause(.5);
end

% --- Executes on button press in pause.
function pause_Callback(hObject, eventdata, handles)
% hObject      handle to pause (see GCBO)
% eventdata    reserved - to be defined in a future version of MATLAB
% handles      structure with handles and user data (see GUIDATA)

```