Compact Sensor System for Monitoring Neonatal Development using a Pyroelectric Approach

NSF Summer Undergraduate Fellowship in Sensor Technologies
Ugonna Ohiri (Computer Engineering), University of Maryland, Baltimore County
Advisor: Dr. Jay Zemel

ABSTRACT

Neonates lack the ability to communicate information regarding their physiological state; therefore neonatologists need proper equipment to be able to monitor their health. [1] The lack of mobility has limited the usefulness of previous devices. To be able to simultaneously monitor significant physiological parameters of these neonates, a compact and reliable sensing device is required. This project proposes the development of an attachable breathing sensor on a baby bottle cap using a pyroelectric approach. The breathing sensor, composed of polyvinylidene difluoride (PVDF) film with electrode attachments is integrated onto a rigid ring. The goal of this sensor design is to reduce the sensor area while being able to detect timing relative to the neonate's sucking signal. The change in temperature is linearly proportional to the sensor output voltage. This device provides a viable solution for the correlation between breathing and sucking data. Using these results, neonatologists can improve their monitoring and analysis of neonatal development.

Table of Contents

3. INTRODUCTION

Every year, more than half a million babies in the United States, approximately 1 in every 8, are born prematurely. Most preterm deliveries occur spontaneously without a known cause. [1] Some of these at-risk infants require intensive care and thus could spend up to several months in the hospital. Prematurity leads to underdevloped lungs, thus reducing the chance of postnatal survival. This immaturity leads to irregular breathing activity. Consequently, neonatologists at the Children's Hospital of Philadelphia (CHoP) are monitoring and studying the breathing patterns of these at-risk neonates. These researchers have been using a bulky and immobile. sensing device to measure the correlation between simultaneous breathing and sucking signals. During the summer of 2011, Poddar designed a pyroelectric breathing sensor to monitor the relationship between change of film temperature and output current during the feeding process. [2] Using the Ohm's Law relationship,

$$V(t) = R \bullet i(t) \qquad \text{(Eq. 1)}$$

an output voltage can be calculated. The sensor was combined with a pressure sensor to monitor sucking and breathing signals simultaneously. This project proposed to further develop the pyroelectric sensor by reducing the sensor area while detecting timing relative to the neonate's sucking signal. It was made of a polyvinylidene diflouride film.

The NeoNur device is designed to collect inputs from the variation of film temperature on the breathing sensor. An instrumentation amplifier is used to offset the sensor signal to handle only positive inputs. The flash memory on-board stores measurements from the sensor and a RS232 connector and appropriate software transfers the data to a PC for further analysis.

4. BACKGROUND

During the early 1930's, Murphy and Thorpe at The University of Pennsylvania Gynecean Hospital Institute developed an apparatus to monitor the frequency response of respiratory movements of newborns. [3] They were able to determine that a gradual expansion occurs in newborn lungs post-birth. By making make telling observations of physiological measurements, the researchers were unable to deduce the correlation between respiratory movements and other external factors.

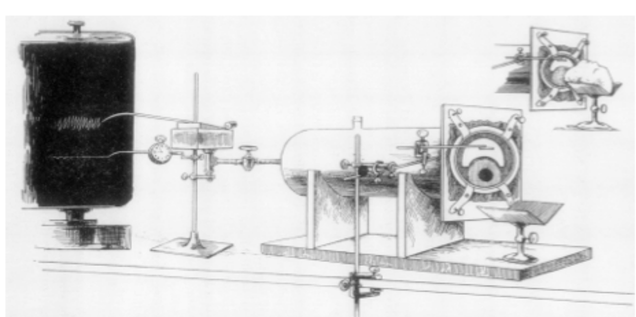


Fig. 1. Murphy and Thorpe Apparatus for Measurement of Rate and Depth of Respiratory Movements of Newborn Infant

Several decades later, Chernick *et al.* at The John Hopkins University, Department of Pediatrics and Environmental Medicine studied twenty-two premature infants on measurements of “end-tidal carbon dioxide tensions and arterial PCO_2, pH, and bicarbonate” (breathing/blood tests respectively). [4] They were able to determine that regular breathing began during a post conception age of 40 weeks.

More recently in 2011, Cooper *et al* [5] completed a sucking assessment of fifty-six full term infants using an Infant Nutritive Sucking Apparatus. The apparatus incorporated a capillary tube for metered flow of a nutrient. Their results showed that sucking responsiveness is based on the maturity of an infant.

Previous apparati had the capability to eventually implement a pyroelectric breathing monitor. This project aims to further accomplish this. The next several subsections describe the concept behind pyroelectricity and the transduction from one form of energy into another.

4.1 Pyroelectric Effect

The pyroelectric effect is the relationship between thermal and electrical activity of a material. Equation 2 relates film charge to film temperature:

$$Q(t) \sim T(t) --> Q = Py \bullet T(t) \qquad \text{(Eq. 2)}$$

where *Q(t)* represents the induced charge on the capacitive plates and *T(t)* represents the change in temperature of the material. Pyroelectricity is a phenomena closely related to ferroelectricity and piezoelectricity. All ferroelectric materials are pyroelectric and all pyroelectric materials are piezoelectric. The main difference in pyroelectricity is that the change of temperature causes opposite sides of the crystal to change its orientation. This increase of temperature leads to a change in electrical polarization of the material. This polarization leads a voltage across the crystal. The total pyroelectric coefficient, *Py*, measured at constant stress, is defined as the summation of the pyroelectric polarization coefficients and thermal expansion coefficients from the secondary pyroelectric effect. Constant stress is defined by the material’s ability to deform or expand thermally. Typically, calculating the primary pyroelectric effect can be difficult. Therefore, the secondary pyroelectric effect, also known as the piezoelectric effect, can be easily calculated by its constant parameters (e.g thermal expansion and elasticity) [6].

When an electric field is present in a pyroelectric material, the direction of the induced charges can change. Equation 3 represents the total sensing response *D* measured as charge per unit area on the capacitive film plates:

$$D_{ij} = \varepsilon E_{ij} + P_{ij} \qquad \text{(Eq. 3)}$$

where ε represents the dielectric permittivity of the pyroelectric material, E_{ij} represents the electric polarization, and P_{ij} represents the pyroelectric polarization. Equation 4 represents the change in the sensing response with respect to the change in film temperature [7]:

$$\frac{\partial D_{ij}}{\partial T_{ij}} = \frac{\partial P_{ij}}{\partial T_{ij}} + E_{ij} \frac{\partial \varepsilon}{\partial T_{ij}} \qquad \text{(Eq. 4)}$$

4.1 Pyroelectric Conversion

Pyroelectricity is the spontaneous polarization of a material when heated or cooled. As the neonate simultaneously receives formula and breathes on the sensor, the sensor's crystalline film structure is altered and an electric current is generated in the external circuit. Current flows in one direction when temperature increases and the opposite direction when temperature decreases. When the film is stressed, charges are also induced on the material surface. This transduction from the variation of temperature to output current occurs as the neonate breathes on the pyroelectric sensor. Equation 5 describes this relationship:

$$i(t) = Py \frac{dT(t)}{dt} \qquad \text{(Eq. 5)}$$

where *i(t)* represents the induced current in the external circuit. The current is generated to balance the induced charges on the material's surface.

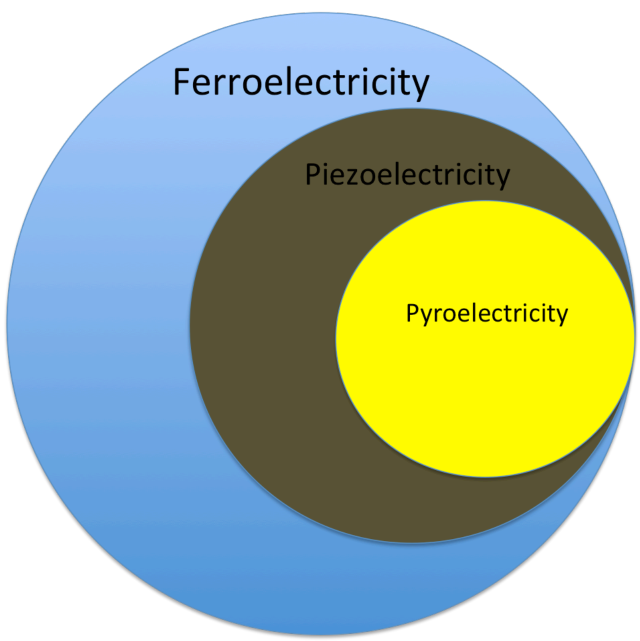


Fig. 2. Relationship between ferroelectricity, piezoelectricity, and pyroelectricity.

5. PROJECT GOALS

The pyroelectric breathing sensor is to be used with the NeoNur feeding system developed. Professors Jay N. Zemel (SEAS, Penn) and Barbara Medoff-Cooper (SON, Penn and CHoP) to monitor feeding characteristics that may relate to critical physiological variables associated with the development of neonates. The scope of the project is to modify the current pyroelectric sensing device. In order to measure breathing, the sensor is attached to a lightweight and mobile baby-bottle sensing device (NeoNur). Upon completion of measurements, sucking and breathing responses as a function of time are stored onto a flash memory chip and transferred to a program-specific software on a PC.

6. DESIGN OF BREATHING SENSOR

6.1 Device Overview

The Neonur measures the generation of pyroelectricity on a breathing sensor attached to a rigid metal ring. The device currently consists of a PIC18F14K50 microcontroller, 1/3N lithium battery, ST95P08M Flash Memory, Boost DC-DC Converter, and other passive componentry. The microcontroller operates as the "brain" of the device by collecting data, controlling timing between successful measurements, powering the light-emitting diodes, and providing analog inputs for the sensor signals.

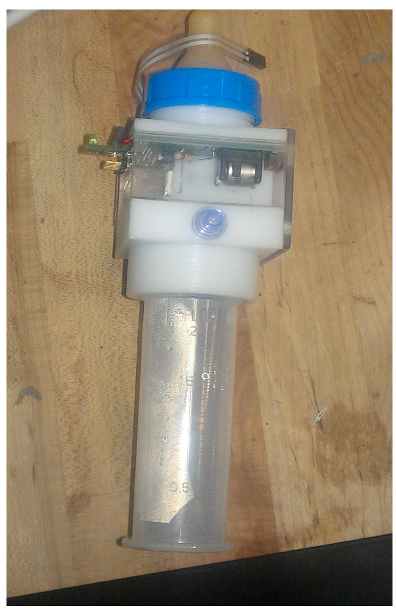


Fig. 5a. Previous NeoNur Apparatus (Summer 2011)

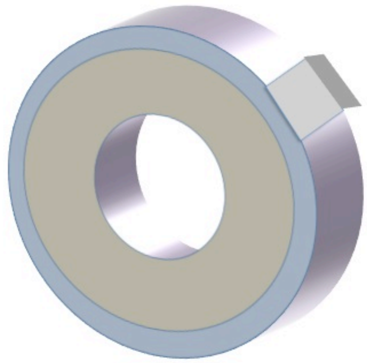


Fig. 6. Three-dimensional model of newly designed baby-bottle ring.

6.2 Sensor Design

6.2.1 Polyvinylidene Film

Polyvinylidene difluoride (PVDF) is the carbon-backbone polymer film used to create the pyroelectric sensor. The film is a plastic material made of vinylidene difluoride. Interchanging CH_2 and CF_2 groups on the polymer chain produces its electrical charges. PVDF and its copolymers have strong pyroelectric properties. The film has a low pyroelectric coefficient but its low thermal conductivity and dielectric constant make them very good responsive sensors.

6.2.2 Methyl Alcohol

Methanol was the chemical substance used to reduce the total area the pyroelectric sensor. This method was able to prevent damage from the Ag capacitive film plates, thus avoiding a short circuit. A cotton swab was moistened to remove the silver paste on the unwanted film. An ohmmeter verified there was no shorting in the film.

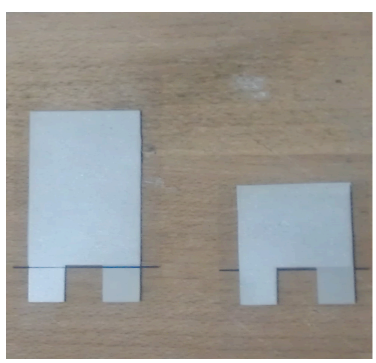


Fig. 7. Original (left) and newly designed (right) pyroelectric sensor for NeoNur

6.2.3 Electrode Leads

Several attempts were made in finding the most efficient method to attach leads to the sensor electrodes. Silver adhesive transfer tape proved to be the most conducive. This was confirmed using an ohmmeter. Two pin connectors were attached to the tape using conductive wire glue and were tightly secured onto a two-pin mechanical housing located on the microprocessor. This was important to be able to decrease the neonatologist's manueverabily of the device.

6.3 Circuit Design

6.3.1 Schematic/Board Design

The schematic and board inside of the Neonur were previously designed by Dr. Zemel's group using EAGLE Computer Aided Design (CAD) software. The individual components were soldered onto a commercialized board shown in Figure 8. Appendix B shows the top and bottom view of a recent circuit board that is under development.

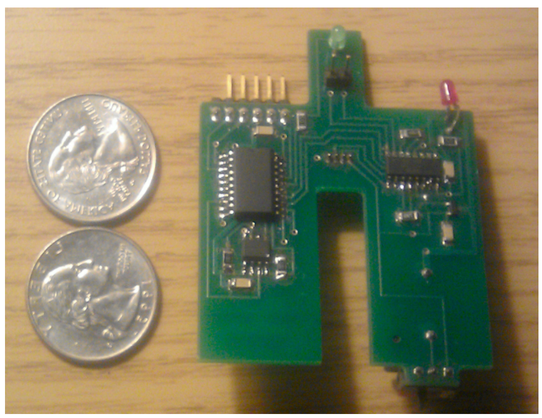


Fig. 8. Completed small microprocessor-based circuit board.

6.3.2 Microcontroller

The Microchip PIC18F14K50 is a USB-Flash microcontroller used to operate the NeoNur. The red LED indicates that the Neonur's is either in its off or on state. The flashing green LED indicates that the NeoNur has reset and cleared its previous measurements. The REG710 is a 30mA 6-pin switched capacitor DC-DC buck-boost converter used the voltage source. The converter produced a low ripple output voltage. It is current-limited, thereby protecting the resistive load across the sensing-circuit. A power switch is connected to the battery, preserving its shelf life. A RS232 cable is a 6-pin peer to peer cable with an adapter board used to transfer measurements from flash memory onto the PC.

6.3.3 Battery

The Duracell 1/3N lithium battery is used to power the NeoNur. The average voltage is ~3V with a nominal internal impedance of 250mΩ @ 1kHz. More notably, the battery is lightweight (Volume = 1.1cm^3), has long shelf life (~7 years), and a wide operating temperature range (-20-60°C). [8] A battery holder secures it.

6.3.4 DC-DC Converter

The REG710 is a 60mA, 5V switched capacitor DC-DC buck-boost converter used as a voltage source. [9] The converter produces a low ripple output voltage.

6.3.5 Instrumentation Amplifier

The INA2126U is a dual single-ended instrumentation amplifier used to regulate the breathing sensor. The high input-impedance signal from the sensor is converted to improve stability and accuracy in the measurements. [10] Equation 6 represents the input voltage to the amplifier:

$$V_{in}(t) = R \bullet L \bullet i(t) \qquad \text{(Eq. 6)}$$

where RL represents a small resistor-inductor load across the pyroelectric sensing output. The magnitude of the input signal V_{in} is proportional to a RL network. The circuit uses an instrumentation amplifier to offset the signal by 1.25V. When taking the derivative of the temperature, the current system cannot handle both a positive and negative signal. Thus the small RL network is generally needed and the gain of the INA compensates for the smaller signal by amplification and signal offset.

6.3.6 Flash Memory

The ST95P08M is a flash memory chip using a serial-in, serial-out peripheral interface to transmit and receive 8 bits of ADC data simultaneously.

6.4 Software Design

The Neonur is programmed using an ADC operational dual-channel for pressure and breathing sensor data to be measured every 5ms.

7. RESULTS

7.1 Breathing Response (Pyroelectric Sensor)

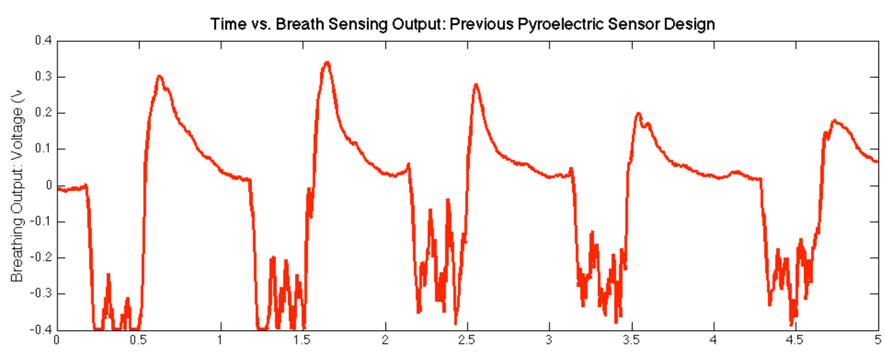


Fig. 10. Time vs. Voltage Output: Previously designed Pyroelectric Sensor

The original pyroelectric sensor dimensions were 3.8cm (H) × 1.4cm (L). The data shows a periodic response from about 0.5-5 seconds. The sensor saturated a little over 0.3V on the second full breath.

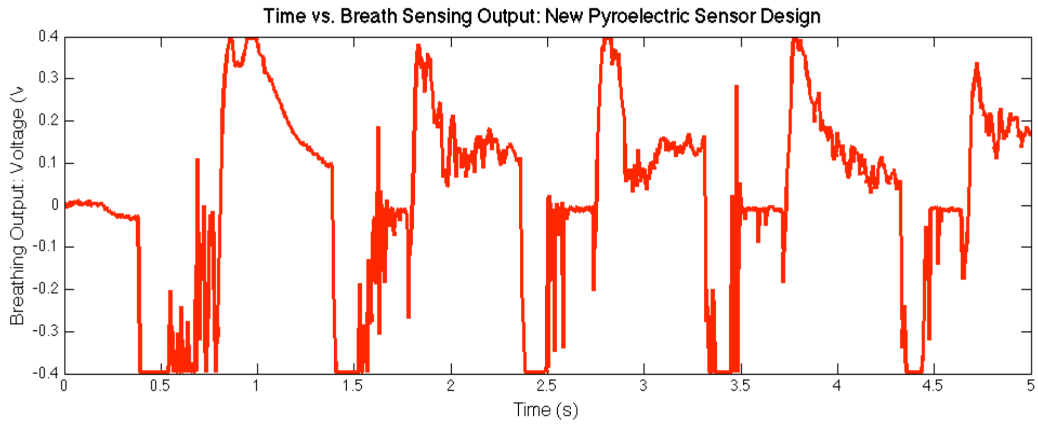


Fig. 11. Time vs. Voltage Output: Newly designed Pyroelectric sensor

The newer pyroelectric sensor dimensions were scaled to 2.2cm(H) × 1.2cm(L) Using the pyroelectric relationships, the sensor output was expected to be higher compared to the previous. A smaller film area leads to a smaller induced charge on the capacative plates, thus leading to a larger output voltage. The sensor response proves to be consistent to the previous design.

7.2 Breathing Response (NeoNur)

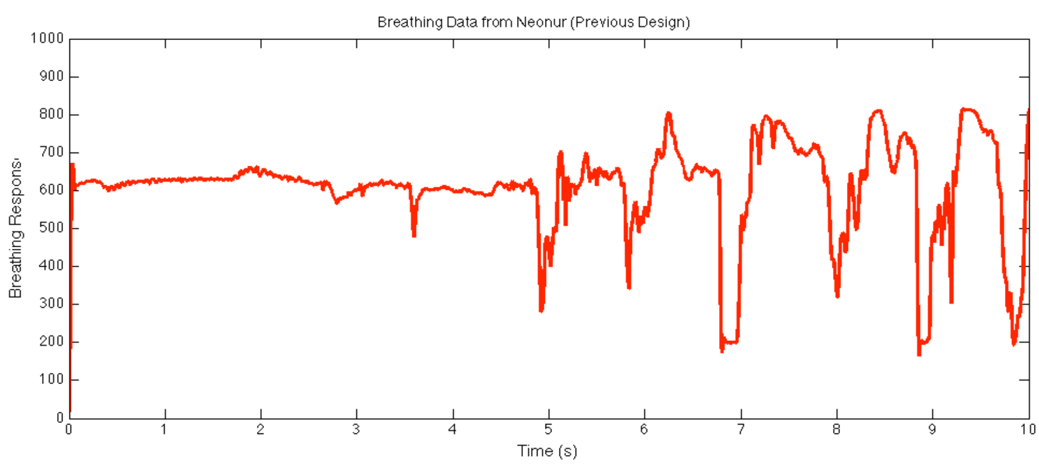


Fig. 13. Time vs. Breathing Output for NeoNur using previous pyroelectric design.

Data was recorded from the Neonur using the previous pyroelectric design. A stable 3rd-order Butterworth low-pass filter was used to flatten the measurements, passing low frequency values while attenuating higher spikes in the data. The order of the filter is defined as the maximun delay to create each output sample. A frequency of 10kHz (~10sec) was measured with a cut-off frequency of 2kHz (~2sec). The first major spike occurs at about 5 seconds. This could have occured from the adjustment of air to receiving liquid from the bottle. In addition, mucus could have been accumulated in the throat when gasping for oxygen during the next breath transition. This could explain the major drops occurring before the 7 and 9 sec mark.

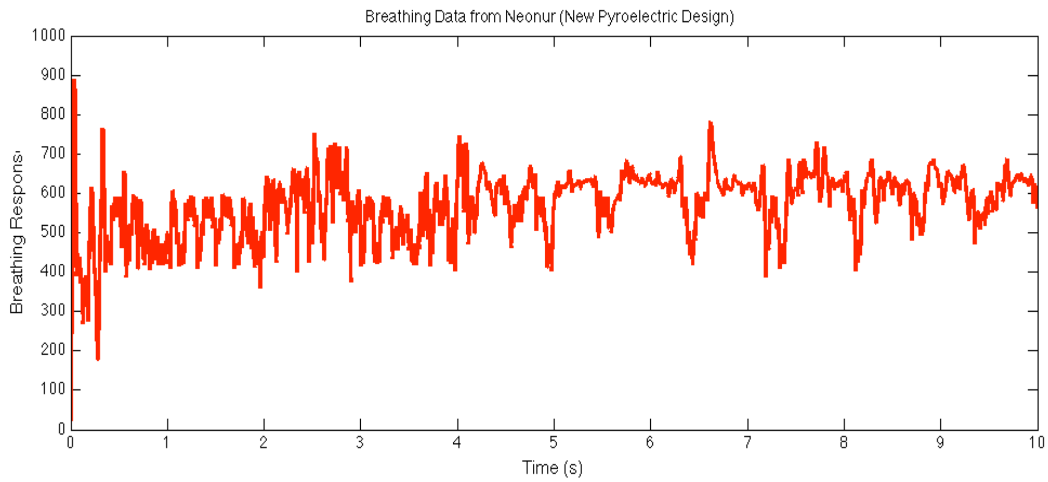


Fig. 14. Time vs. Breathing Output for NeoNur using new pyroelectric design.

Data was recorded using the new pyroelectric design. The same Butterworth filter was used to flatten the measurements. The data shows periodicity around the 5sec mark. This adjustment is similar to Figure 13. The consistency between the two designs show this pyroelectric design is viable for monitoring the breathing patterns of premature and at-risk neonates. Nonetheless, the signal had evident noise. A goal for the near future would be adding hardware on-board for low-pass filtering to smoothen the real-time raw data.

8. CONCLUSIONS

In this study, minimizing the area of the breathing sensor was successfuly completed, while alse detecting timing relative to a neonate's sucking signal. The approach was done using pyroelectricity. This new design allows neonatologists at CHOP to manuever and operate the NeoNur easily. Results show this device has promise as a reliable tool for use with premature and at-risk neonates in the hosptial. However, more development is needed before the device can be fully implemented on a national level.

9. FUTURE WORK

9.1 Software

Currently, the NeoNur has two operational ADC channels for breathing and sucking measurements. Presumably in the near future, the Neonur will be equipped with additional sensors to learn more about the physiological characteristics of neonates.

9.2 Hardware

At the current stage, the NeoNur has a working pressure and breathing sensor. A critical part for the future development of this device is to be able to add more components on-board, therefore enhancing the sensing component but also maintaining its small area. As developments arise for the NeoNur, such as implementing low-pass filtering, additional circuit prototyping and boards will need to be fabricated and tested.

9.3 Device Testing

Another undergraduate and I performed the measurements for the Neonur. The device was tested primarily in the laboratory. In the near future, the Neonur will be integrated into hospitals nationwide.

10. ACKNOWLEDGMENTS

I would like to thank Dr. Jay Zemel and Dr. Jan Van Der Spiegel for knowledge and insight in the development of my research project. I would also like to thank the National Science Foundation for their funding and support that has allowed me to partake in the SUNFEST Program.

11. REFERENCES

[1] CDC Features – Premature Birth. [Online], Available: http://www.cdc.gov/Features/PrematureBirth/

[2] P. Poddar, *A Pyroelectric Approach to the Mobile Monitoring of Neonatal Breathing.* SUNFEST 2011, Center for Sensor Technologies, Univ. of Pennsylvania, 2011.

[3] D. P. Murphy, E. S. Thorpe, "Breathing Measurements on Normal Newborn Infants." J Clinical Investigation, vol. 10, pp. 545, 1931.

[4] V. Chernick, F. Heldrich, M. E. Avery, "Periodic Breathing of premature infants." *J Pediatric,* vol 64, pp. 330, 1964.

[5] B. Medoff-Cooper, W. Blker, JM Kaplan, "Sucking patterns and behavioral state in 1- and 2-day-old full term infants", J Obstet Gynecology Neonatal Nursing, vol. 39, pp. 519-524, 2011.

[6] S. Lang, "Pyroelectricity: From Ancient Curiosity to Modern Imaging Tool," Phys Today, vol. 58, pp. 31, 2005.

[7] University of Cambridge: Variation of Polarisation with Temperature. [Online], Available: http://www.doitpoms.ac.uk/tlplib/pyroelectricity/variationofpol.php

[8] 1/3N 3.0 Volt Lithium Battery Datasheet, Duracell. [Online], Available: http://www.medicbatteries.com/media/tech_specs/1_3n1.pdf

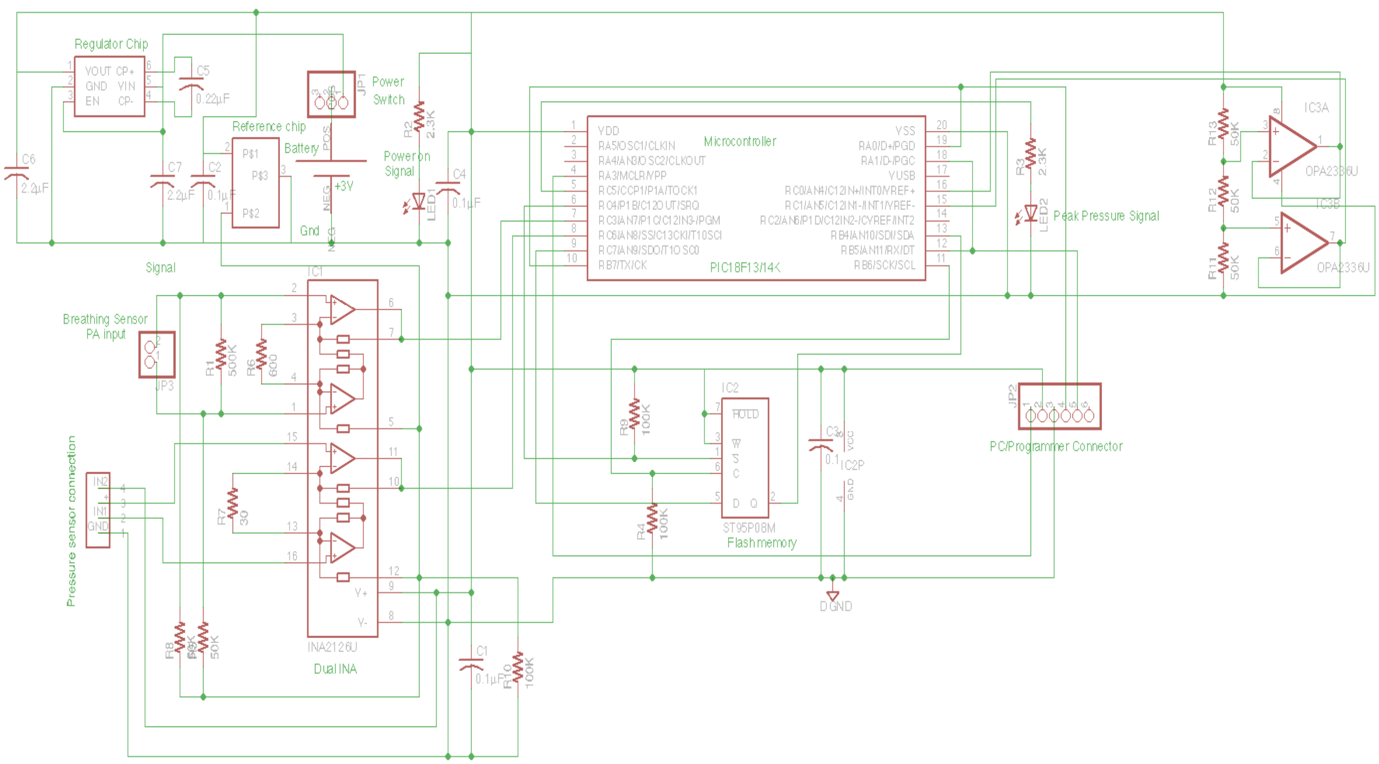
[9] REG710 Datasheet, Texas Instruments. [Online], Available: http://www.ti.com/lit/ds/sbas221g/sbas221g.pdf

[10] INA2126U Datasheet, Texas Instruments. [Online], Available: www.datasheetcatalog.org/datasheet2/0/000uql1uahp038k3ork48pzrpr7y.pdf

12. APPENDICES

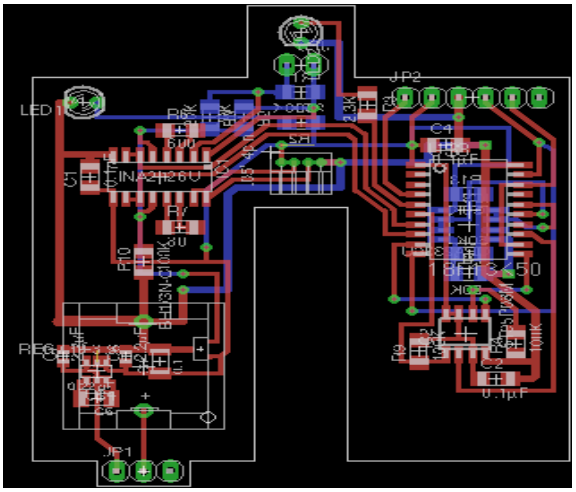
12.1 Appendix A

NeoNur Schematic

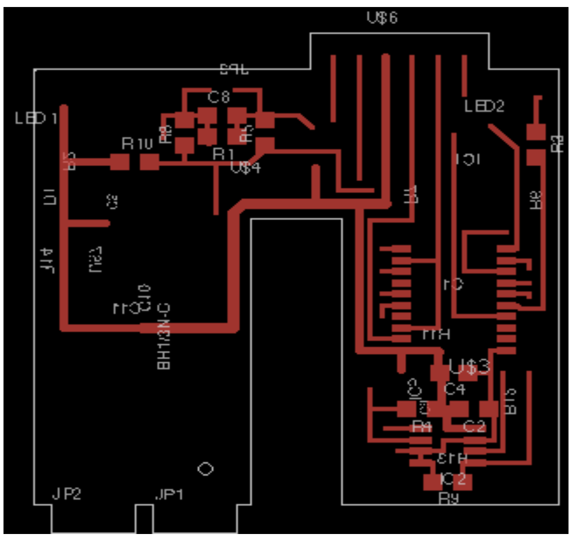


12.2 Appendix B

NeoNur Board (Full)



NeoNur Board (Top)



NeoNur Board (Bottom)