

EEL 4914 Senior Design

Final Design Report

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PAMELA: Pulse Acquisition and Monitoring Equipment for Living Applications

Team Name: PULSERS

Submitted by:

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Project Abstract:

The goal of our project is to measure three heartbeats on the same test subject and be able to continuously chart/analyze the timing differences among the heart beats. The continuous heart rate will be determined and displayed as well. With this data, numerous other plots can be displayed (trajectory, change in heart rate over time, etc.)

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Features/Objectives:

This design is for a specific application. Its main function is to investigate how three heart beats relate to the health condition of the test subject. The data will be recorded for further analysis. The user will be able to determine their Beats Per Minute (BPM), view the average width of each pulse and the timing delay between the different beats. The user will have two methods for viewing the BPM, the on-board LCD screen, or from a computer which receives the serial data. A potential case study would be to collect data on a physically fit, healthy subject with no known organ deficiencies and to collect data on an unhealthy subject with known organ deficiencies. A general application of this product is to analyze one's heart rate and interpret the data accordingly. Existing products do not satisfy the needs of our specific application. Some current products on the market include hospital heart rate monitors which implement IR sensors, wrist watch BPM monitors, etc.

The electronic pulse acquisition device will provide a unique and accurate method for acquiring heart rate data for medical studies. The main features include:

- Three sensors detecting the pulse
- USB cable for easy access data acquisition
- Easy to read graphical displays with pertinent health information through computer based software
 - Differences in delay between the three different sensed pulses
 - Individual R-R-interval values
 - Constant Beats per Minute (BPM) monitor

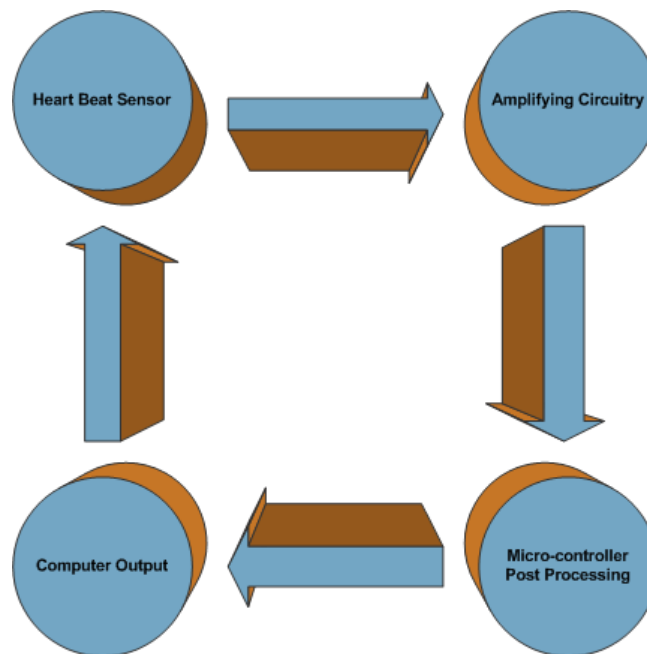


Figure 1. Overview of the Pulse Acquisition System

Analysis of Competitive Products:

Our two competitors are the MITes (MIT Environmental Sensor) Heart Rate Monitor [5] and the COSY Digital Heart Beat Monitor [6]. The MITes HRM (heart rate monitor) implements an industry standard Polar chest-strap transmitter and receiver. The transmitter sends out a beating pulse while the actual MITes generic board receives this heart beat signal, calculates the BPM and sends it back to the MITes receiver. Voltage regulators are implemented to convert 5V down to 3V for the input of the device. This MITes unit is contained within a pillbox and costs \$95.50 per 50 units. [5]

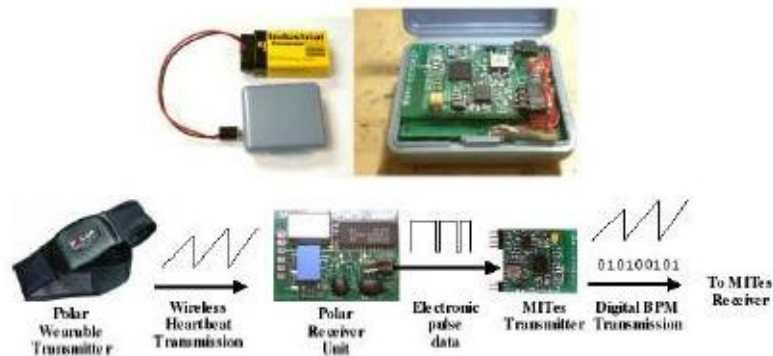


Figure 2. MITes Heart Beat Monitor [5]

The COSY Digital Heart Beat Monitor features an IR finger/earlobe clip sensor to monitor the heartbeat. It is a micro-controller based system which indicates the pulse via LED display and a piezoelectric beep. It features a bar graph to indicate the best sensor position on the finger/earlobe and costs \$100 per unit. [6]



Figure 3. COSY Digital Heart Beat Monitor [6]

Although both of these products are listed as competitors, they do not deliver the specific tasks that this electronic pulse acquisition device offers. The device in this paper acquires three heart beat pulses and analyzes the differences in pulses for medical purposes. Instead of implementing an IR sensor, this device features three force sensors which capture the heart beat signal. This device is expected to cost nearly \$170 per unit.

Technical Concepts:

The main objective of our project is to construct a product which can provide data which can be interpreted to diagnose the health condition of a test subject depending on the timing differences of three diverse heart beats. Preliminary testing consisted of attempting to detect the heart rate with an IR detector (LTR-301) and emitter (LTE-302) [1]. Unfortunately, the results were unacceptable and an alternative to IR sensors was sought out. An expert's opinion led to testing force sensors (102-1223-ND). It was determined that these force sensors would indeed detect a pulse.

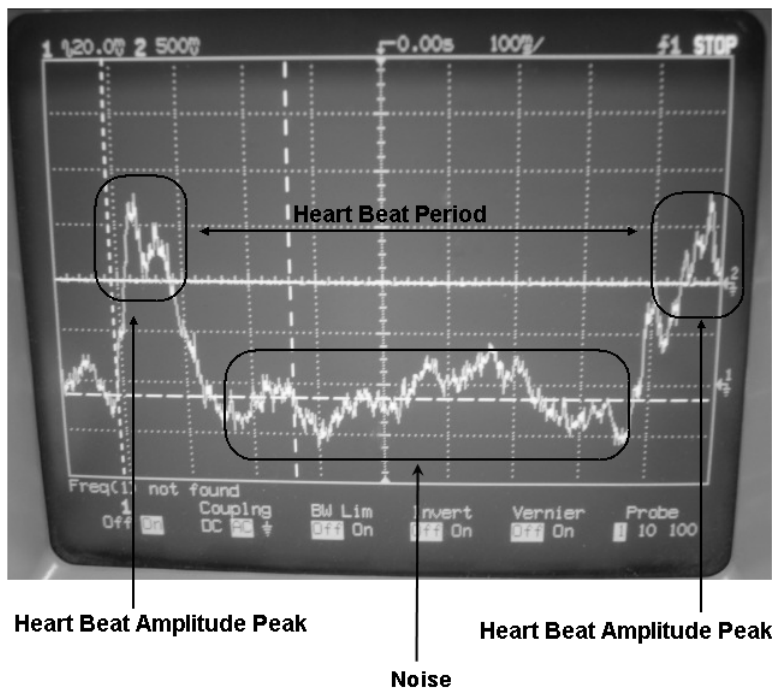


Figure 4. Annotated Oscilloscope Reading of a Heartbeat via Force Sensor (SF-4)

As noted in Figure 4, the signal contains a consistent amount of noise. Essentially, the force sensor acts as a potentiometer with a resistance range of 100,000 kOhms (no force) down to nearly 1 kOhm (1.5 kg force) [2]. When placed in series with a resistor and a 5V DC source the force sensor detects a pulse with amplitude of approximately 60 mV. This signal will need to be amplified with an amplifying circuit prior to being read by an A/D converter.

In order to accommodate the project's goal, our final design consists of three force sensors and supporting circuitry. A low-pass RC filter with a cut-off frequency of 15Hz is used to remove most of the unwanted noise. Band-pass filters were simulated and determined insufficient, as can be seen in Appendix A. An AC Coupler is used to remove any difference in constant pressure between the sensors.

Figure 5 shows that the three analog signals will be converted to a digital signal via an A/D converter and will then be post processed by the microcontroller and provide the appropriate data for a computer output. The Atmega family is the microcontroller type chosen for this project. An Atmel Atmega 324P was used because it supplies enough A/D, I/O and UART ports for this application. Data will be sent to a computer via the microcontroller's UART output. It is then fed to an FTDI Serial-to-USB converter (FT232RL) which attaches to the computer.

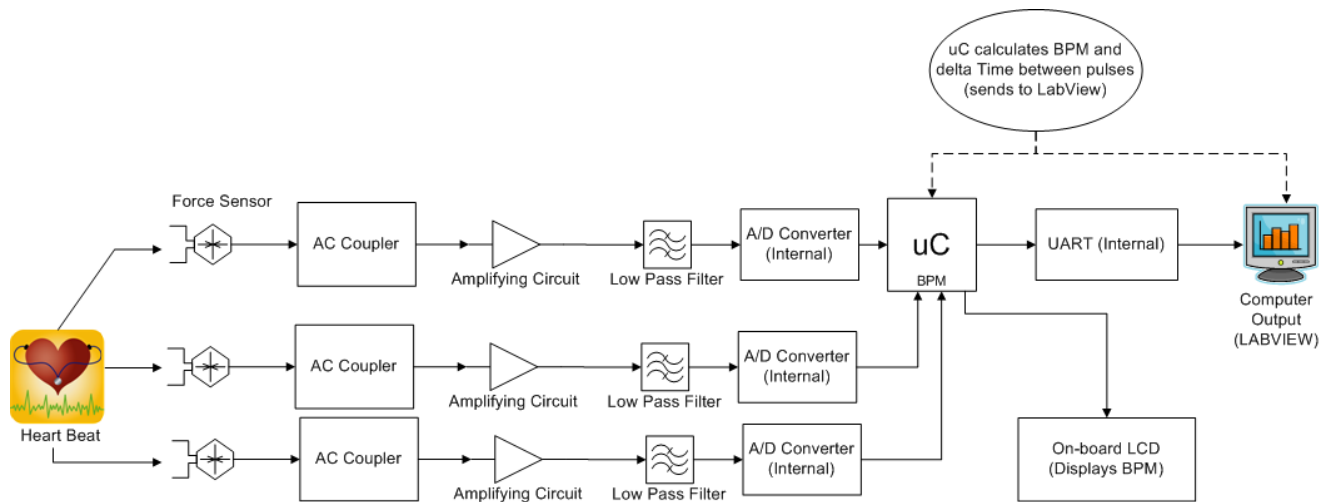


Figure 5. Technical Linear Schematic of PAMELA Architecture.

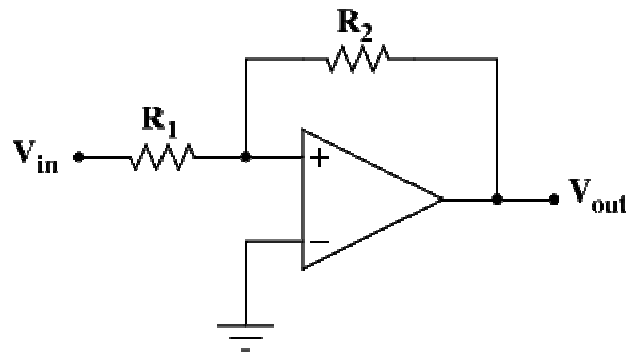


Figure 6. A simple op-amp schematic representation of a Schmidt Trigger [3]

To calculate the Beats Per Minute and collect the pulse start and stop times the concept of a Schmidt trigger was implemented in the microcontroller code [3]. A Schmidt trigger is a comparator circuit (see Figure 6) which outputs a high voltage while the input voltage is higher than a designated high preset value. It outputs a low voltage while the input voltage falls below a designated low preset value. If the input voltage is between these two preset values, then the output is unaltered. This comparator concept will be used in software to determine the BPM (beats per minute) of the test subject.

National Instrument's LabVIEW is an extensive part of the data analysis. LabVIEW is a development environment which implements a graphical programming language to accomplish a task. Users can drag and drop block diagrams which serve as visual subroutines and interconnect them with wires. Data is input to each subroutine or interface and output through the wires towards the following block diagrams [4].

Architecture:

The sensors used were CUI, Inc.'s SF-5 square pressure sensor (DigiKey P/N: 102-1225-ND). The sensor is made of a Piezo-resistive material and as seen in Figure 7 [2], as pressure is applied to the sensor the resistance decreases. The values in Figure 7 are derived from the SF-2 square pressure sensor, a 2 mm² sensor rather than the 5 mm² sensor used in this project. The SF-2 and SF-5 sensors share the same data sheet. A voltage divider circuit was created with a 1 MOhm resistor. With the pressure sensor operating near 100 to 250 gf the resistance range of the sensor would range from 100 KOhm to 5 MOhm. Assuming this range of pressure is applied when taking a pulse, then the voltage divider would yield the largest range in voltage change. The output of this voltage divider is taken through a voltage following operational amplifier, to eliminate the effects of current on the circuit.

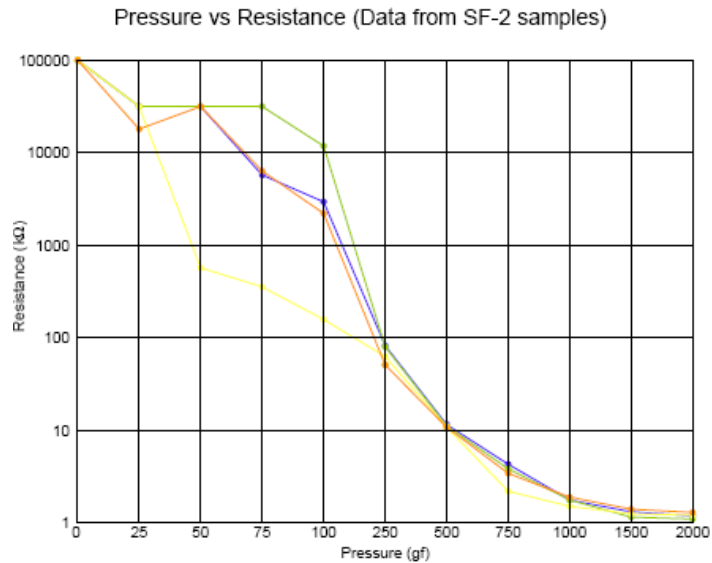


Figure 7. SF-2 Square Pressure Sensor, Pressure vs. Resistance

The output of the first operational amplifier is then attached to a DC blocking (AC coupler) capacitor and biased at 2.5V with a two 1 MOhm voltage divider circuit and placed at the positive terminal of the amplifying operational amplifier. The negative terminal is biased at an analog ground 2.5V, used for the other sensors with a feedback circuit that contains two potentiometers for setting gain. One potentiometer is for setting the coarse gain (100 KOhm) and the other for fine gain (10 KOhm). The output of the amplifying operational amplifier is passed through a low-pass RC circuit with a cut-off frequency of 15 Hz ($R = 100$ KOhm, $C = 0.1$ uF). The output of the low-pass filter is then used as the input to the on-chip Analog-to-Digital Converter in the Atmega 324P micro-controller.

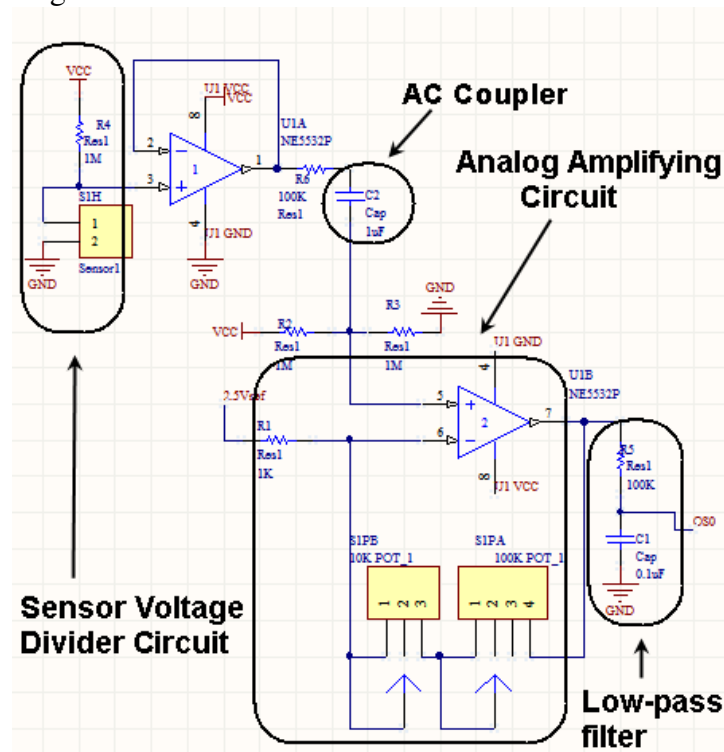


Figure 8. Analog Circuitry for One Sensor

The micro-controller analyzes the Analog-to-Digital data to calculate the Beats Per Minute and the start/stop times of each pulse. After these calculations, the user can view the Beats Per Minute calculated via each sensor by interfacing with the device and the on-board Liquid Crystal Display (LCD) screen. In addition, all of the calculated data is sent out of USART0 (Universal Synchronous/Asynchronous Receiver/Transmitter) at 230,400 baud. A 14.745 MHz external oscillator was used to ensure 0% error at such a high baud rate. The data is sent out of USART0 in the following format:

```
TX(<data0>,<BPM0>,<start0>,<stop0>,<data1>,<BPM1>,<start1>,<stop1>,<data2>,<BPM2>,<start2>,<stop2>)\r\n
```

This format is catered towards transmission to National Instrument's LabView. The "TX(" and ")r\n" statements specify the beginning, and end, of transmission respectively. The first data block, <data0> is the current Sensor0 reading. <BPM0> is the calculated Beats per Minute for Sensor0. Start0 is the start time of a pulse and Stop0 is the stop time of a pulse. This pattern repeats for each of the three sensors.

When LabView receives the data, using the Instrument I/O Assistant, it plots the raw Sensor data and outputs each BPM. There is then extensive logic to calculate the delay between each sensors beats and the width of each heartbeat pulse. The width of each pulse is used to calculate the R-interval of each heartbeat. The R-interval is, in essence, the unique period of each heart beat, typically measured from peak-to-peak. The R-interval in this project is measured from the base of a peak to the base of the next peak. The delay between each pulse allows for a visualization of the delay in milliseconds between one pulse measurement versus another. The LabView output is also stored into a comma delimited file for further analysis. Figure 9 shows the software flow chart, which has been abbreviated to include only one process, but the processes are repeated for each of the three sensors. Figure 10 shows a portion of the LabView Block Diagram which contains the logic portion of the code. Figure 11 shows a portion of the LabView Front Panel which contains the output portion of the code. Appendix [D] (software PDF version only) shows the entire Block Diagram and Front Panel, including sub-VIs (Virtual Instruments).

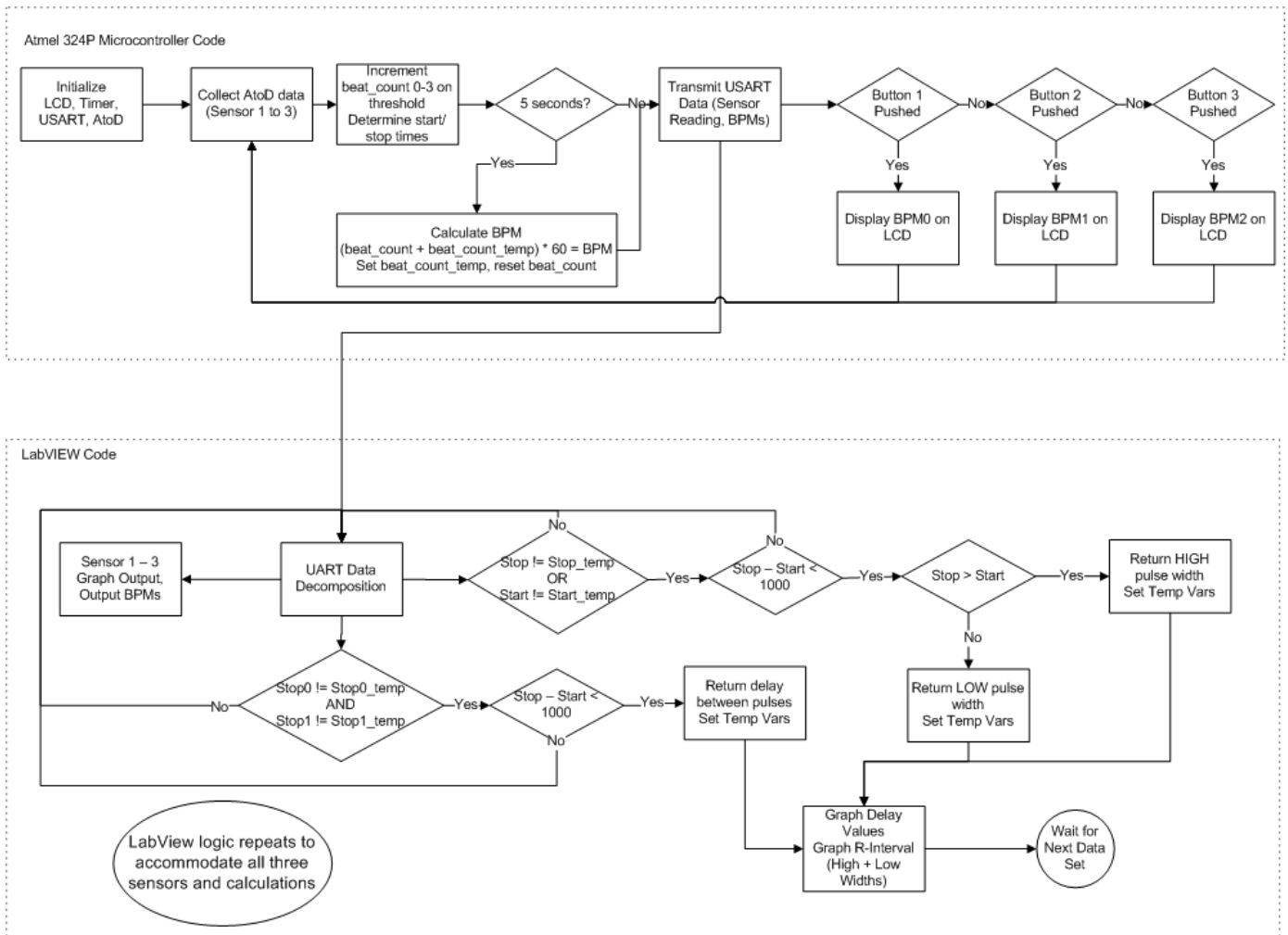


Figure 9. Micro-controller and LabVIEW Software Flow Chart

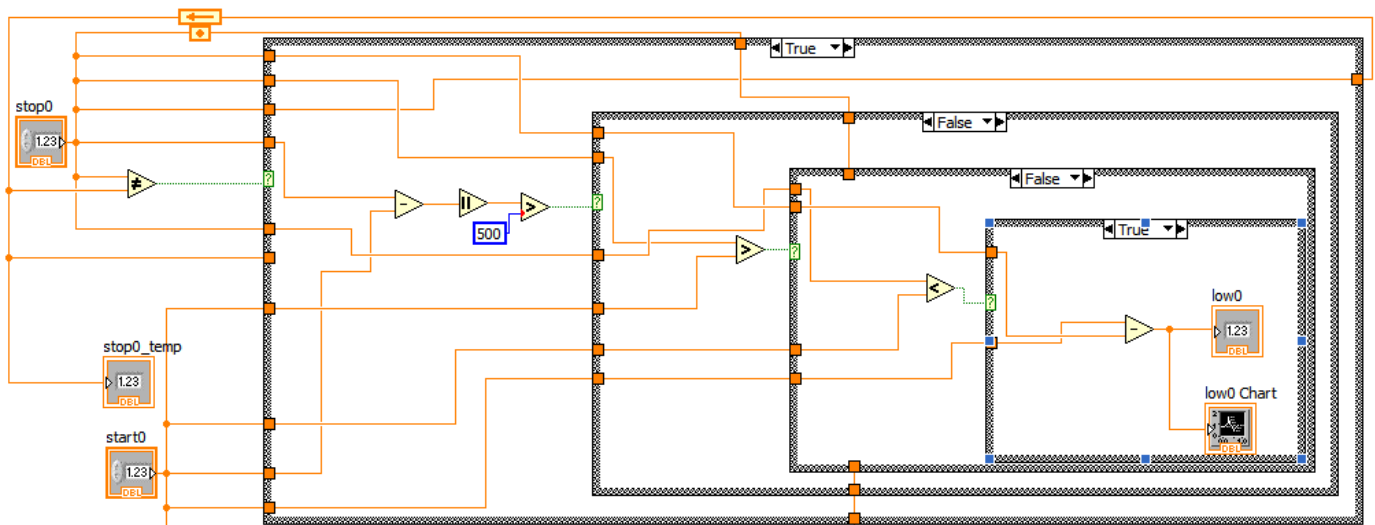


Figure 10. Portion of the LabVIEW Block Diagram Logic

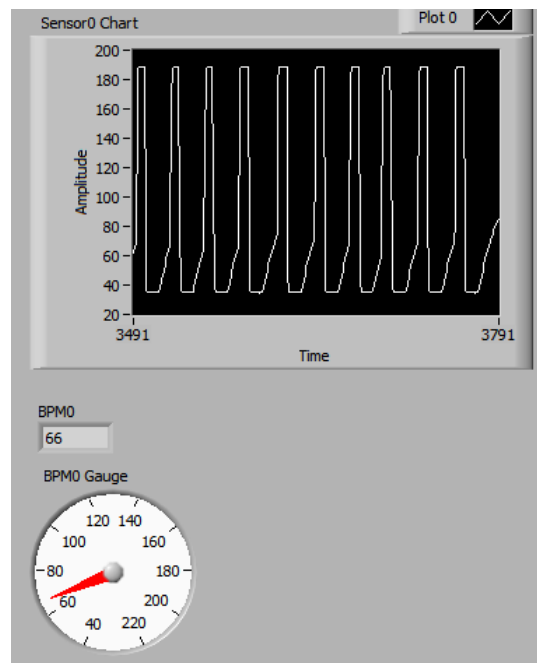


Figure 11. Portion of LabView Front Panel Output

The programming language used to program the micro-controller was C, adapted for use of the Atmega line of products. The programming interface used was AVR Studio 4 with WinAVR-20071221 as the backend interface to the GCC compiler. All of the programming code used to accomplish the project's goals can be found in Appendix [C] (software PDF version only). Appendix [B] contains the entire circuit design and layout, created with Altium Designer 6.8.

User Manual:

This interface is quite easy to use. The user simply needs to have LabView pre-installed with the Software VI's loaded. The user then should connect their computer to the Printed Circuit Board (PCB) via a A-to-B USB cable and choose the proper COM settings in National Instruments Measurement & Automation application. Namely, the desired baud rate is 230,400 baud, with 8 data bits, Odd Parity (O), One (1) Stop Bit and no Flow Control. Simply put; 230400 8-O-1, None.

It may also be necessary for the user to choose the proper COM port in the Software VI. They can do this by double-clicking the Instrument I/O Assistant and choosing the proper instrument. Upon correct setup, the device will display the data as received from the sensors. There is also an Enable button in the VI to turn on/off data recording.

To receive proper data from the sensors the user should place the sensors on any artery they choose and applying the correct back pressure with their fingers to allow pulses to be properly sensed. If there is not enough gain, it can be adjusted by turning the fine and coarse gain potentiometers which sit near the sensor connectors. Given enough practice, the user will be able to view their pulses and retrieve valuable information about each pulse.

In addition to viewing the output in LabView the user can view a sensor's BPM reading on the on-board LCD screen. The user is to push one of the three buttons, one button for each sensor, which will display the last BPM reading for 3 seconds on the LCD screen.

Suggested Improvements:

Because of the nature of the sensors being pressure dependent, an amount of pressure must be applied to the sensor in order for it to receive the small pressure a pulse applies. This applied pressure blocked by the AC coupler, however because three different gain circuits are used, it is not feasible to contrast and compare the amplitudes of the pulses. A sensor which would allow for the same measurements this device performs, along with measuring an accurate amplitude for each pulse would be ideal. One possible sensor is a simple infrared sensor; others include electrodes and oxygen sensors.

Analog potentiometers were used which do not allow for high-fidelity tuning. Digital potentiometers such as Analog Devices AD5200 [7] would allow for very accurate resistances, and therefore gain. However, they add significant overhead by with more circuitry and programming necessary.

A smaller, more compact device would allow for portability and decrease costs significantly. The initial board was dimensioned at 7 inches by 7.5 inches. The board was re-designed to be 5 inches by 5 inches and the layout can be seen in Appendix [B]. Assuming no further changes to circuitry, this board can be populated and used accordingly.

The pressure sensors do not currently allow this, as they are sensitive to movement. However, if the sensors were to allow movement this device could be made portable by decreasing the size of the instrument (mentioned above) and by adding on-board data recording. With on-board data recording, a wireless transmission to the computer could be added for quickly and easily allowing for data transport. Utilizing the Bluetooth protocol would be an ideal example.

Bill of Materials:

Product	Part Number	Quantity	Price Per Unit	Total
Atmega 324P	ATMEGA324P-20PU	1	\$6.02	\$6.02
Force Sensors	SF-5L	3	\$6.45	\$19.35
Operational Amplifier	NE5532N	4	\$0.13	\$0.52
FT232RL	604-00043	1	\$4.02	\$4.02
USB Connector	KUSBX-BS1N-B	1	\$0.71	\$0.71
1.8 MOhm Precision Resister	TNPW12061M80BYEA	8	\$9.17	\$73.36
47 uF Capacitor (Polarized)	UVR1V470MDD	1	\$0.20	\$0.20
100 nF Capacitor (Ceramic)	K104K15X7RF53K2	10	\$0.06	\$0.60
Toggle Switch	108-1AS2T2220-EVX	1	\$2.90	\$2.90
LabView (Student)	N/A	1	\$80.00	\$80.00
Miscellaneous	N/A	N/A	\$50.00	\$50.00
Total	-	-	-	\$237.68

Table 1. Bill of Materials

Division of Labor:

Carlos Manuel Torres Jr.	Mark Oden
Preliminary Research	Preliminary Testing
Design Amplifying Circuit	Design Noise Reduction Circuit(s)
Program LabVIEW & Schmidt Trigger	Program A/D input/output (microcontroller)
Design Final Board	Design Preliminary Board
Test/Debug	Test/Debug
Presentation, Documentation and Meetings	Presentation, Documentation and Meetings

Table 2. Planned Division of Labor

Task/Percentage	Mark Oden	Carlos Torres, Jr.
Preliminary Research	35%	65%
Preliminary Testing	45%	55%
Design Amplifying Circuit	75%	25%
Design Noise Reduction Circuit	25%	75%
Design PCB Board	25%	75%
Populate PCB Board	75%	25%
Design Rev 2. Board	90%	10%
Program Microcontroller	100%	0%
Program LabView	10%	90%
Debugging/Testing	50%	50%

Table 3. Actual Division of Labor

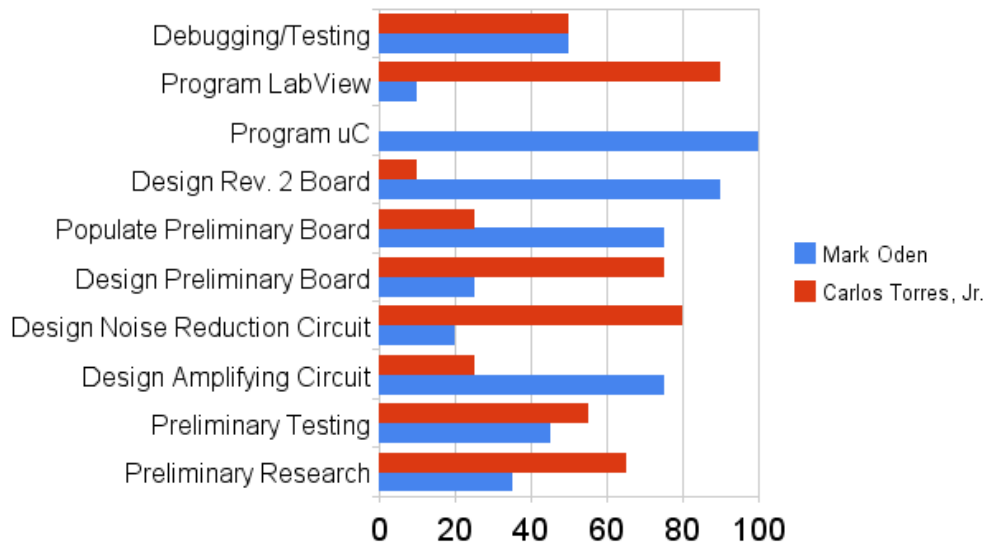


Figure 12. Actual Division of Labor Graph

Timeline:

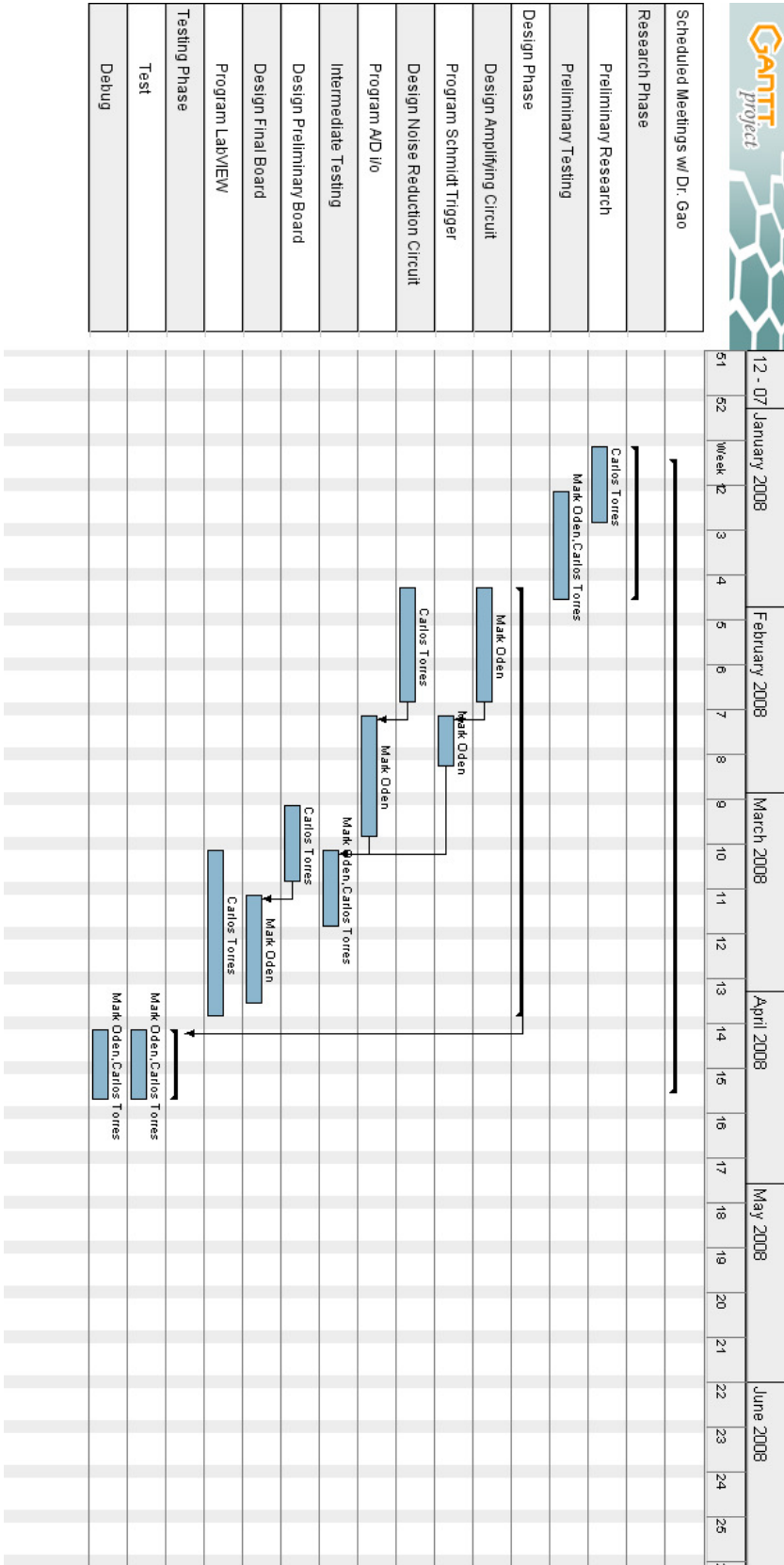


Figure 13. Gantt Chart (Project Timeline).

Applications in Research:

This device allows for an "immediate" output of the current sensor readings, the current BPM calculation, the delay between the sensors and the individual R-R intervals. In research applications this immediate data should be compiled continuously over a long period of time continuously in order to allow for proper analyzation and interpretation. One application is analyzing the R-R intervals over time, otherwise known as Heart Rate Variability (HRV). Prior research [8] indicates that HRV data is a multiscale phenomenon, namely a random fractal. A multiscale, random fractal is characterized by being stochastic yet has long-range correlation with a small part of the signal representing another part or the whole signal. Given a sufficient data set, determining whether it is a random fractal or not can be done by first finding the signal's power spectral density (PSD) and determining the slope of the PSD over many scales of frequency (i.e. 0 to 10,000). Once the slope (M) is determined then the Hurst parameter (H) can be found by performing the simple linear operation: $M = 2H - 1$. If the Hurst parameter is found to be between 0 and 0.5 then the signal can be considered to have antipersistent correlation and be representative of a random fractal.

Figure 14 shows the Power Spectral Density of 588 R-R-interval values recorded from the designed electronic device on an assumed healthy 24-year old male subject. The R-R-interval for each pulse was determined by adding the time the system determined as currently in a pulse with the time between pulses. The PSD was calculated by first performing a Fast Fourier Transform (FFT), then singling out the amplitude by taking the absolute value of each data point and finally squaring the amplitude of each point. The mean R-R-interval value for this data set was approximately 380 ms.

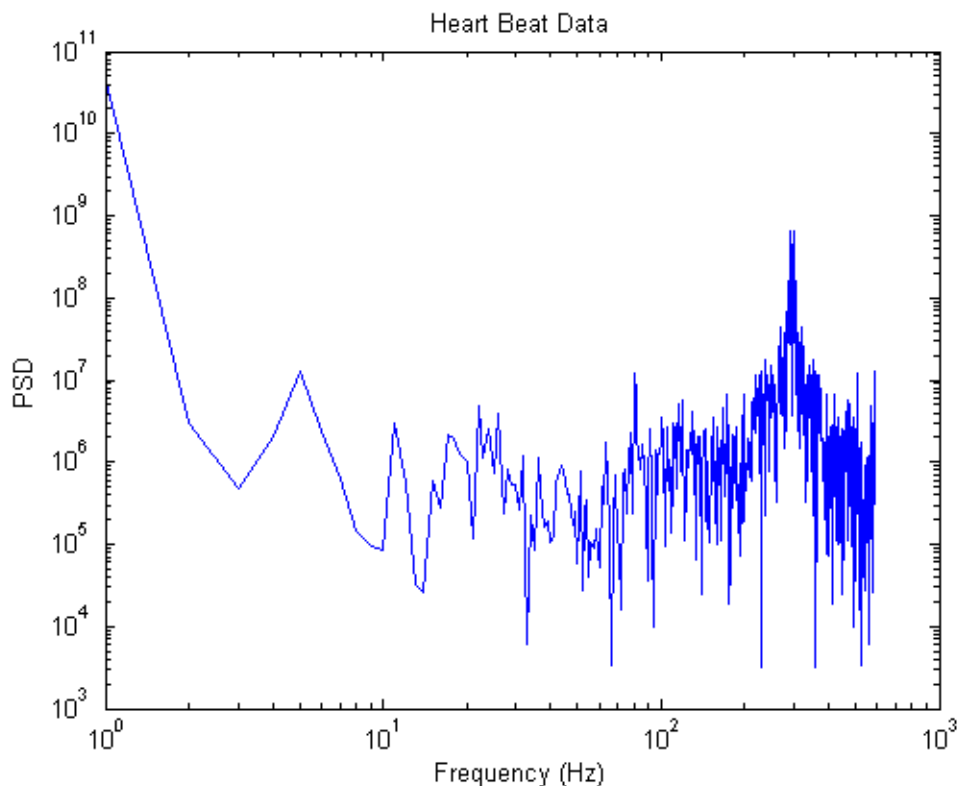


Figure 14. Power Spectral Density plot of 588 point R-R-interval data

With the assumption that HRV data holds the characteristics of being a multiscale random fractal, many analyzing techniques are available. For example, the scale-dependent Lyapunov exponent (SDLE) allows for the analysis of data on a relatively short data set (in the hundreds, to thousands of data points) and allows for the interpretation of random fractal signals. In [8], the authors analyzed 30,000 points of R-R-interval data for each sampled participant in two classes. Data of 18 healthy participants and 15 unhealthy participants

were downloaded from PhysioNet and analyzed by calculating the SDLE, or $\lambda(\epsilon)$. The unhealthy participants were known to have congestive heart failure (CHF). According to the American Heart Association [9] congestive heart failure is defined as a potentially fatal disease "that can result from any structural or functional cardiac disorder that impairs the ability to fill with or eject blood." Figure 15 shows the analysis by [8] of the HRV data set from PhysioNet. The drastic differences in the graphs demonstrate that comparing HRV data amongst healthy and unhealthy participants can allow for the diagnosis of heart related illnesses.

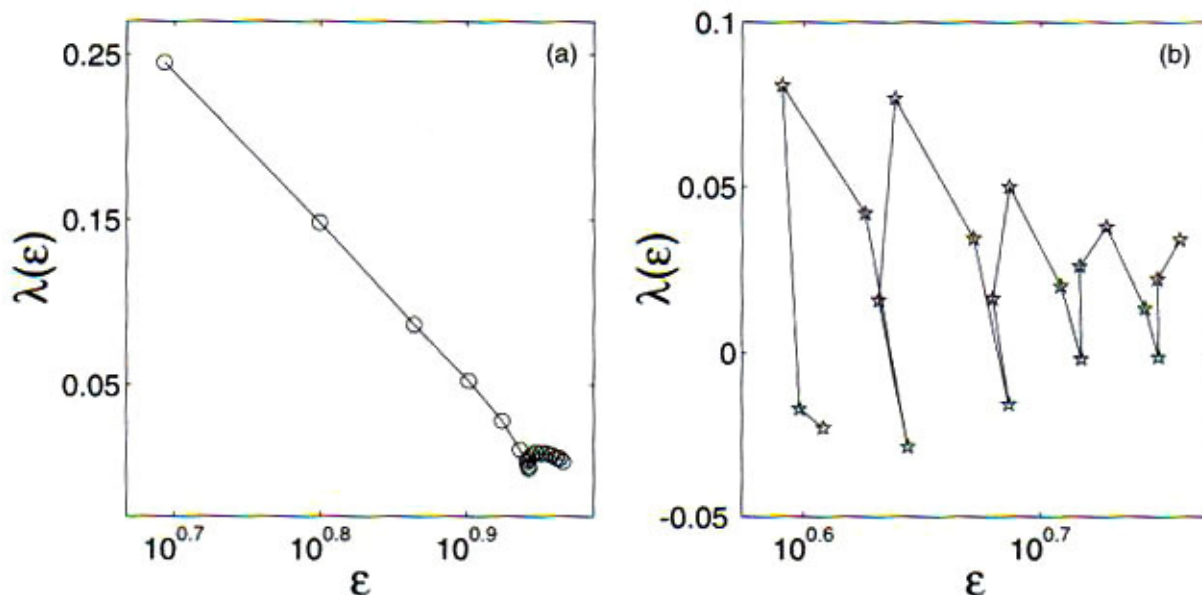


Figure 15. " $\lambda(\epsilon)$ (per beat) vs. ϵ (on a semilog scale) for HRV data of (a) a healthy subject and (b) a subject with CHF" [8]. Used with permission.

In addition to comparing HRV data amongst healthy and unhealthy subjects, HRV data can also be compared between different age groups. In [10] the authors collected 24 hours of HRV data from 114 known healthy participants with ages ranging from 1 to 82 years. 12 echocardiogram (ECG) leads were used in the collection of the data. Through numerous techniques, including PSD analysis as mentioned at the beginning of this section, it was found that as age increases the R-R-interval becomes more stable and less variable. The authors conclude that this may suggest children and young-adults have a "highly adaptive cardiovascular regulatory system" [10]. Other findings by the authors show that female HRV data demonstrate more randomness than males and in both cases the variance increases at night, presumably during sleep. The authors suggest that a higher heart rate variance may be a sign of a healthier subject. The electronic device discussed in this paper is intended to allow for the collection of HRV data from one to three probes. The authors in [10] also show that R-R-interval data for young adults (ages 15 to 39 years) had a mean value of 875 ± 121 ms over 24 hours. The electronic device discussed in this paper found an average R-R-interval of 380 ms on a 24-year old male over approximately 6 minutes.

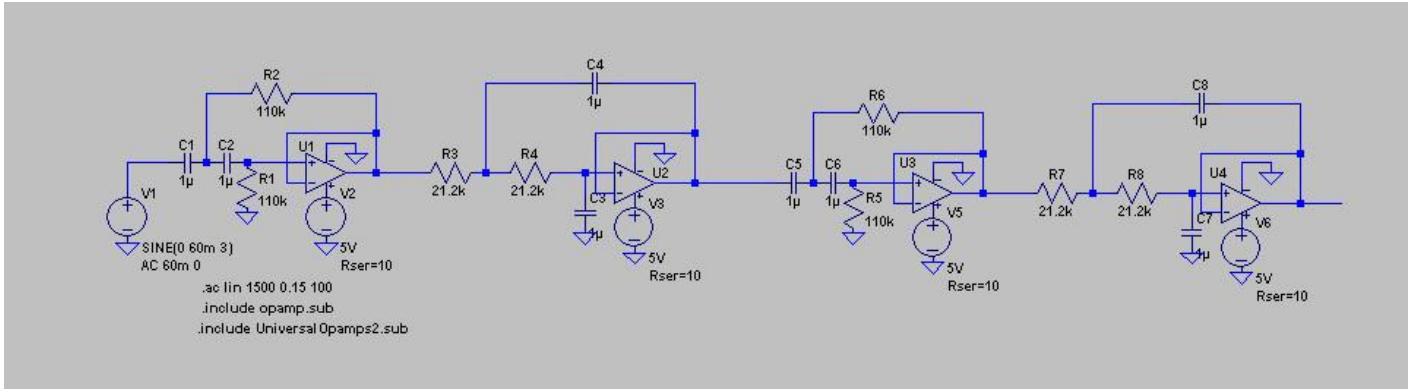
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 Senior Design (EEL 4914) Technical Advisor: Michael Stapleton
 Senior Design (EEL 4914) Teacher's Assistants: Thomas McDonley, Joshua Childs

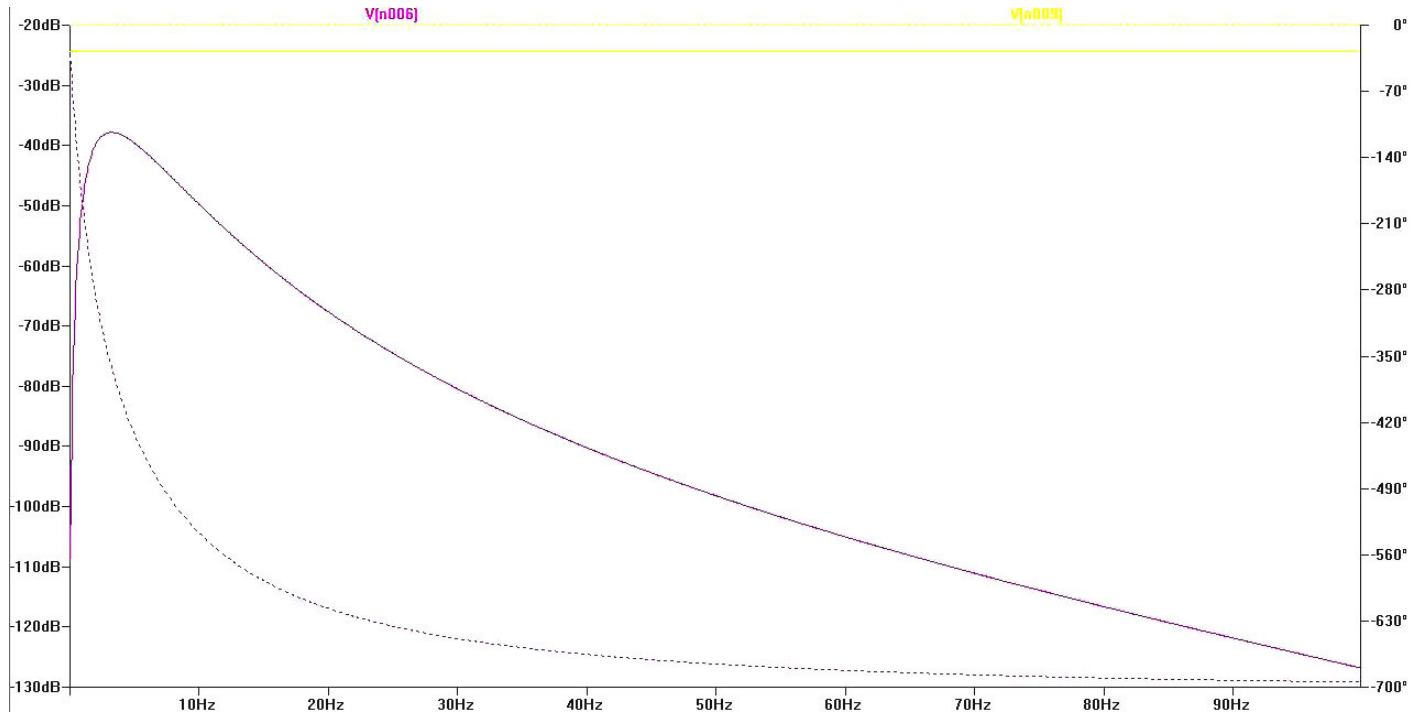
References:

- [1] Lynette Jones, Nikhila Deo, Brett Lockyer, "Wireless Physiological Sensor System for Ambulatory Use," *bsn*, pp. 146-149, International Workshop on Wearable and Implantable Body Sensor Networks (BSN'06), 2006.
- [2] CUI, Inc. SF-X-XX Part Specification Sheet. <http://www.cui.com/pdf/SF-X.pdf>.
- [3] Schmidt Trigger - Wikipedia, the free encyclopedia. http://en.wikipedia.org/wiki/Schmidt_trigger.
- [4] LabVIEW - Wikipedia, the free encyclopedia. <http://en.wikipedia.org/wiki/Labview>
- [5] MIT Media Lab - MITes (MIT Environmental Sensors), <http://web.media.mit.edu/~emunguia/html/mites.htm>
- [6] COSY Digital Heartbeat Monitor, <http://www.cosycommunications.com/Digitalpulsemonitorcatalogue.htm>
- [7] Analog Devices AD5200 Part Specification Sheet. http://www.analog.com/UploadedFiles/Data_Sheets/AD5200_5201.pdf
- [8] Multiscale analysis of complex time series : integration of chaos and random fractal theory, and beyond / Jianbo Gao [et al.] John Wiley & Sons, Inc. 2007.
- [9] Sharon Ann Hunt, et. al. ACC/AHA 2005 Guideline Update for the Diagnosis and Management of Chronic Heart Failure in the Adult. *Circulation*, Sep 2005; 112; e145 - e235
- [10] Sirku M. Pikkujämsä, et. al. Cardiac Interbeat Interval Dynamics From Childhood to Senescence: Comparison of Conventional and New Measures Based on Fractals and Chaos Theory. *Circulation*. Jul 1999; 10: 393 - 399.

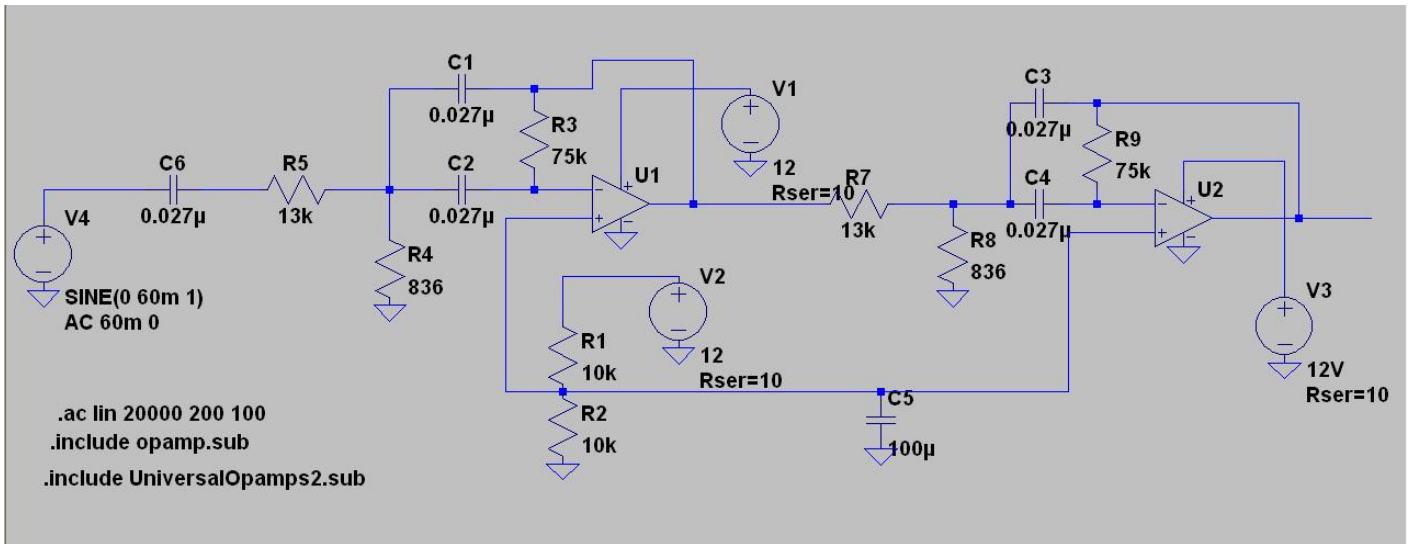
Appendix A. LT. Spice Filter Simulations:



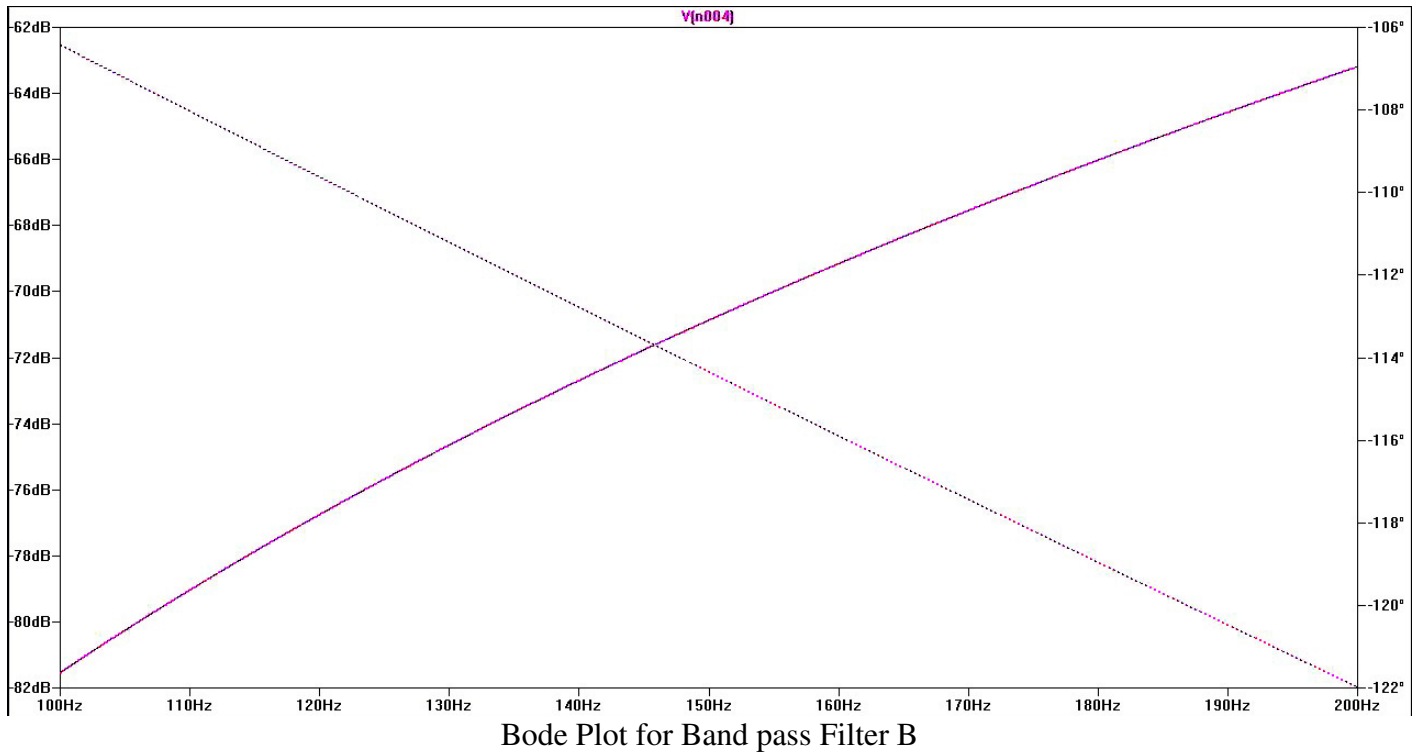
Band pass Filter A

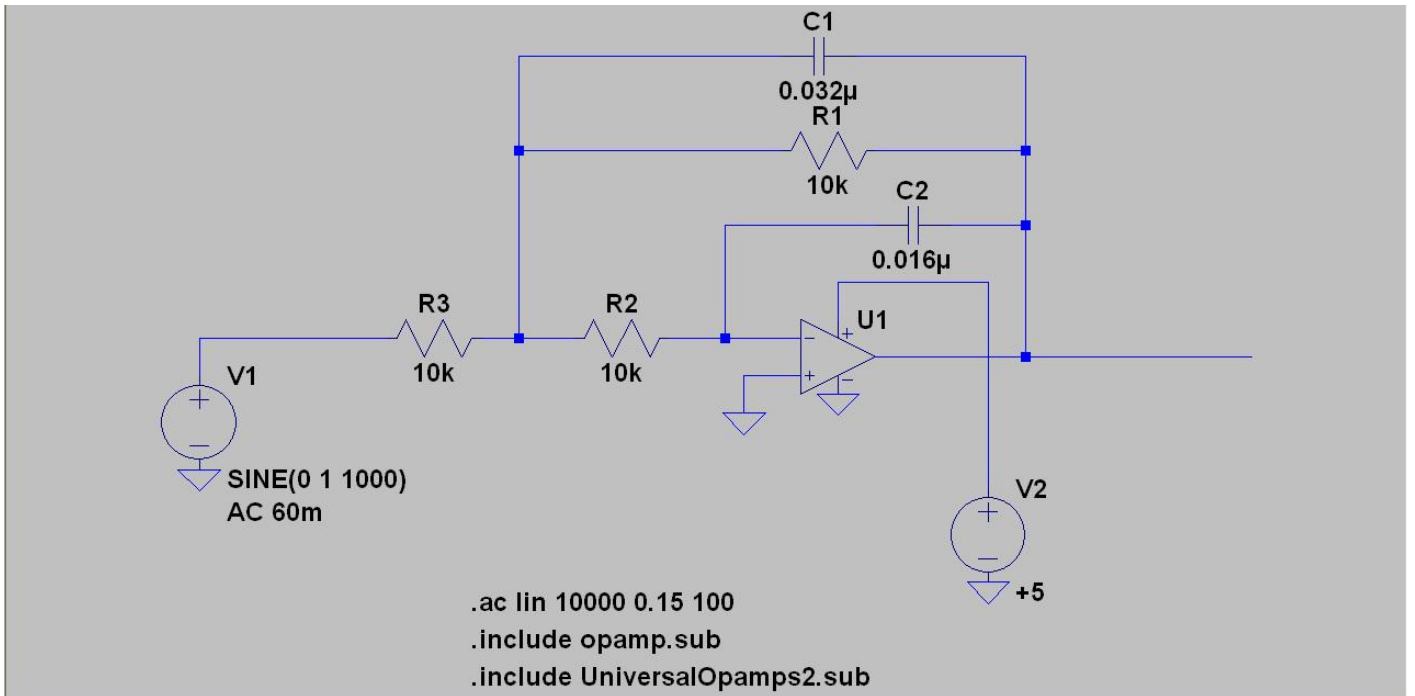


Bode Plot for Band pass Filter A

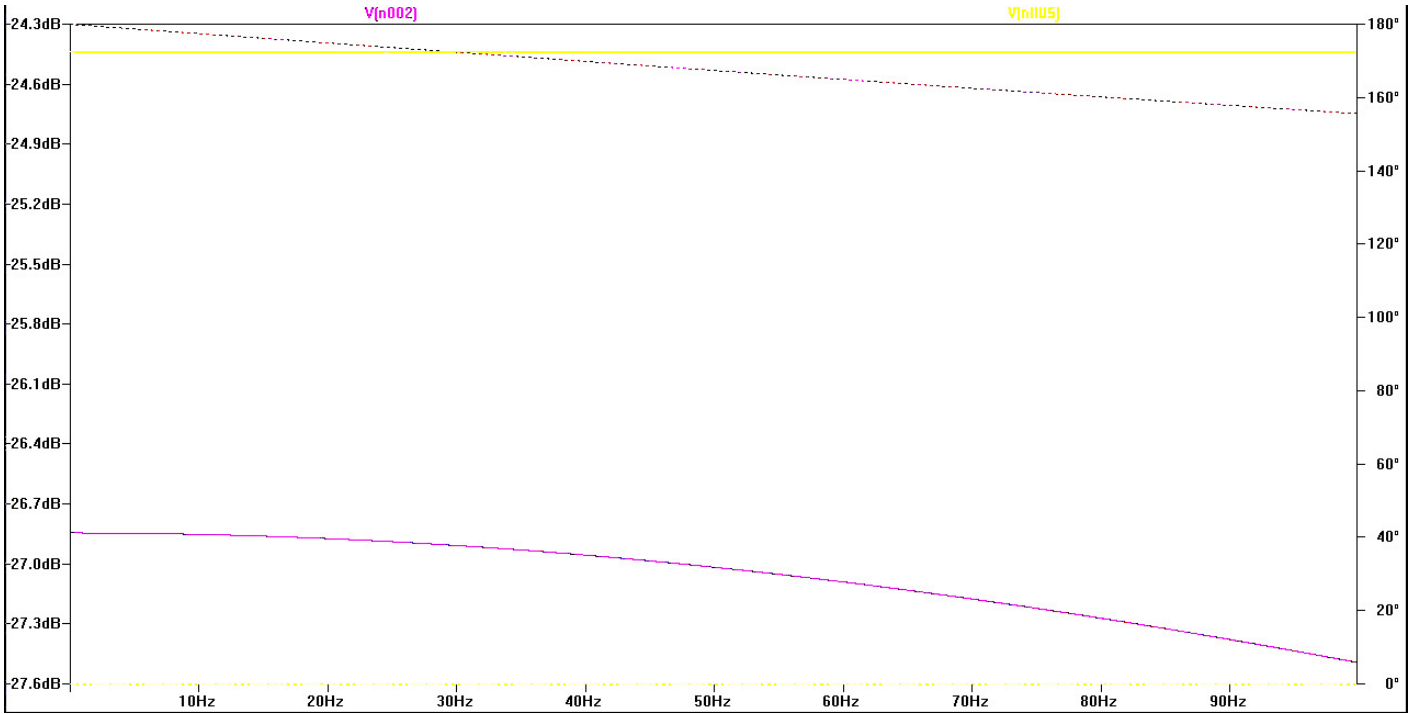


Band pass Filter B



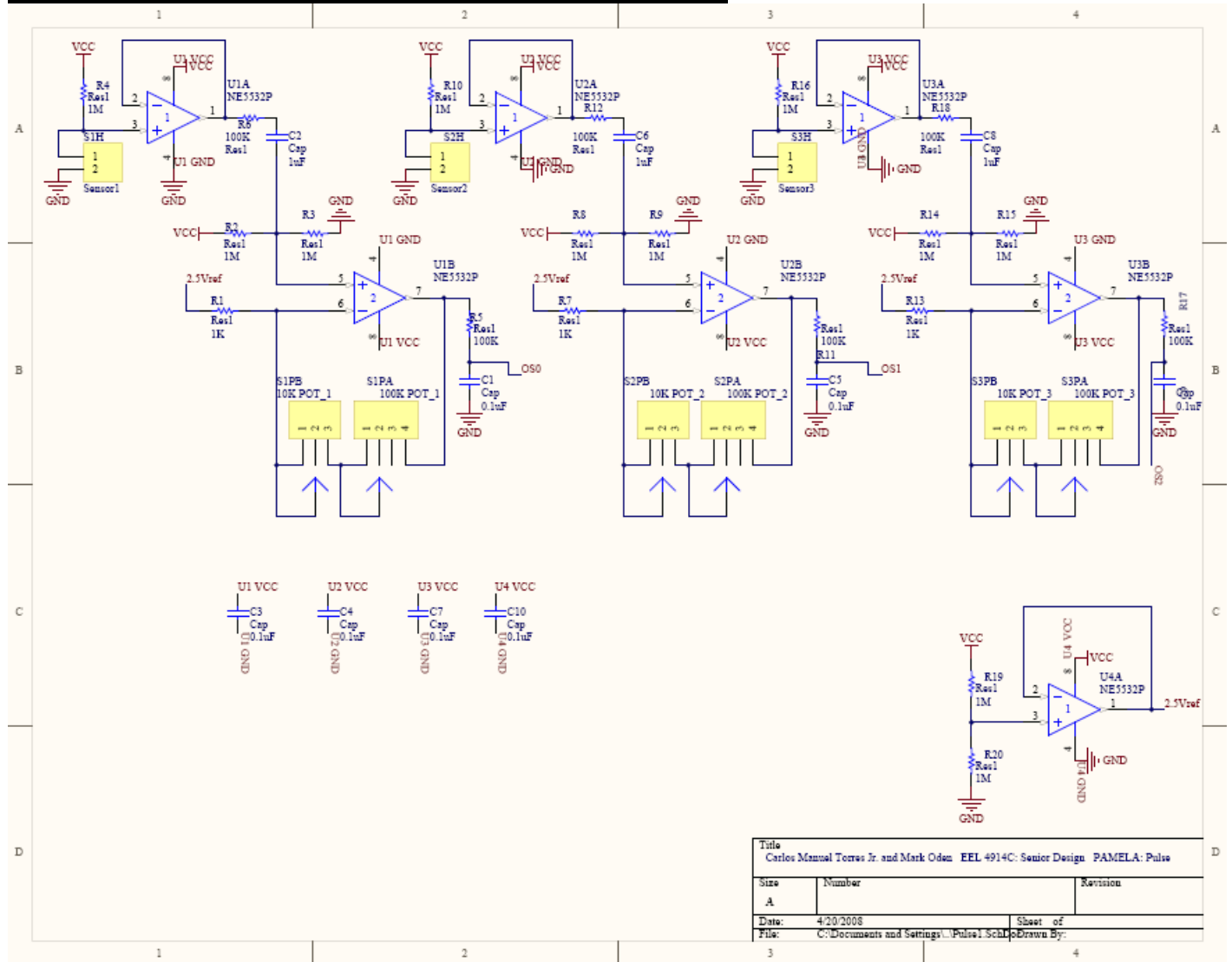


Band pass filter C

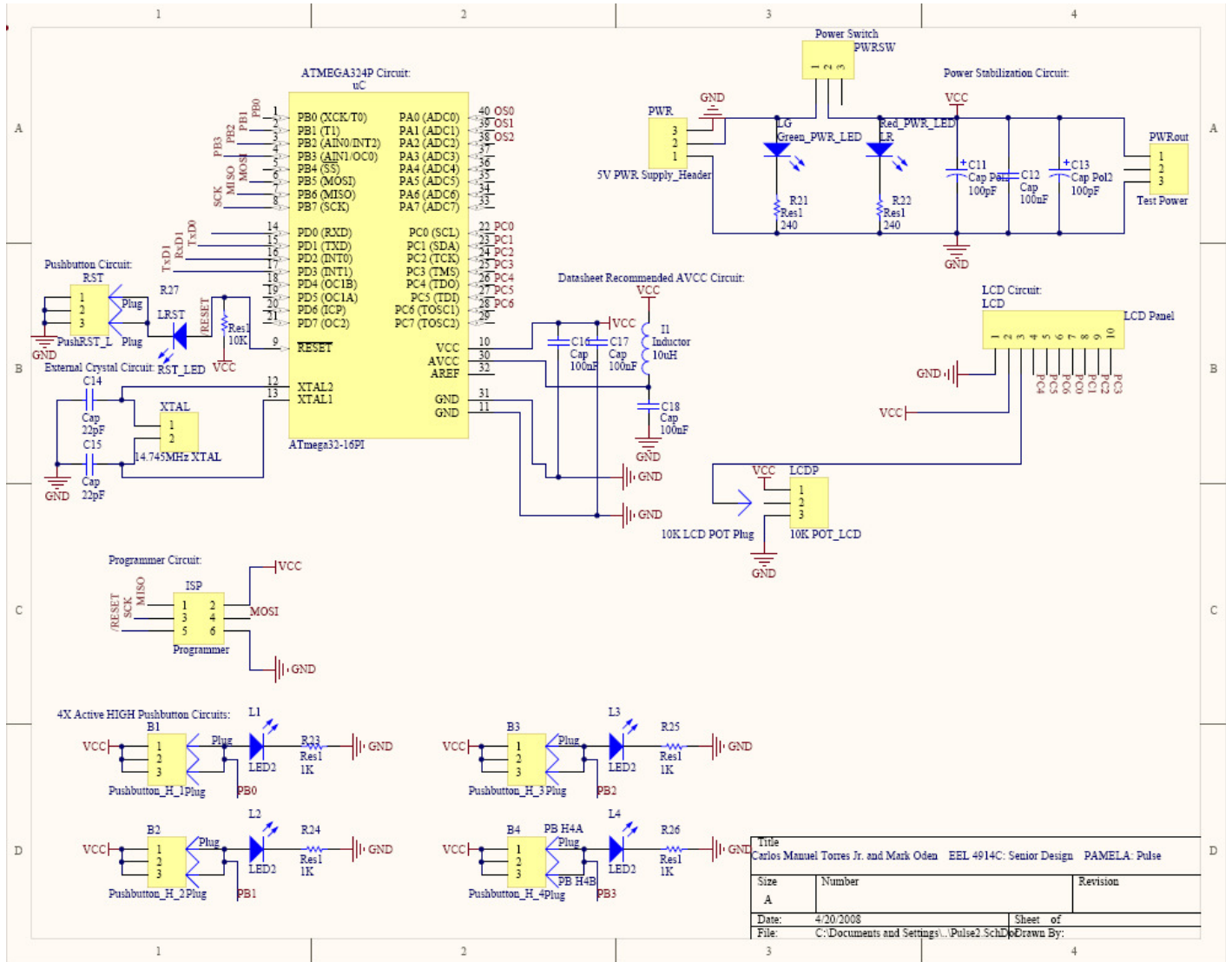


Bode plot for Band pass filter C

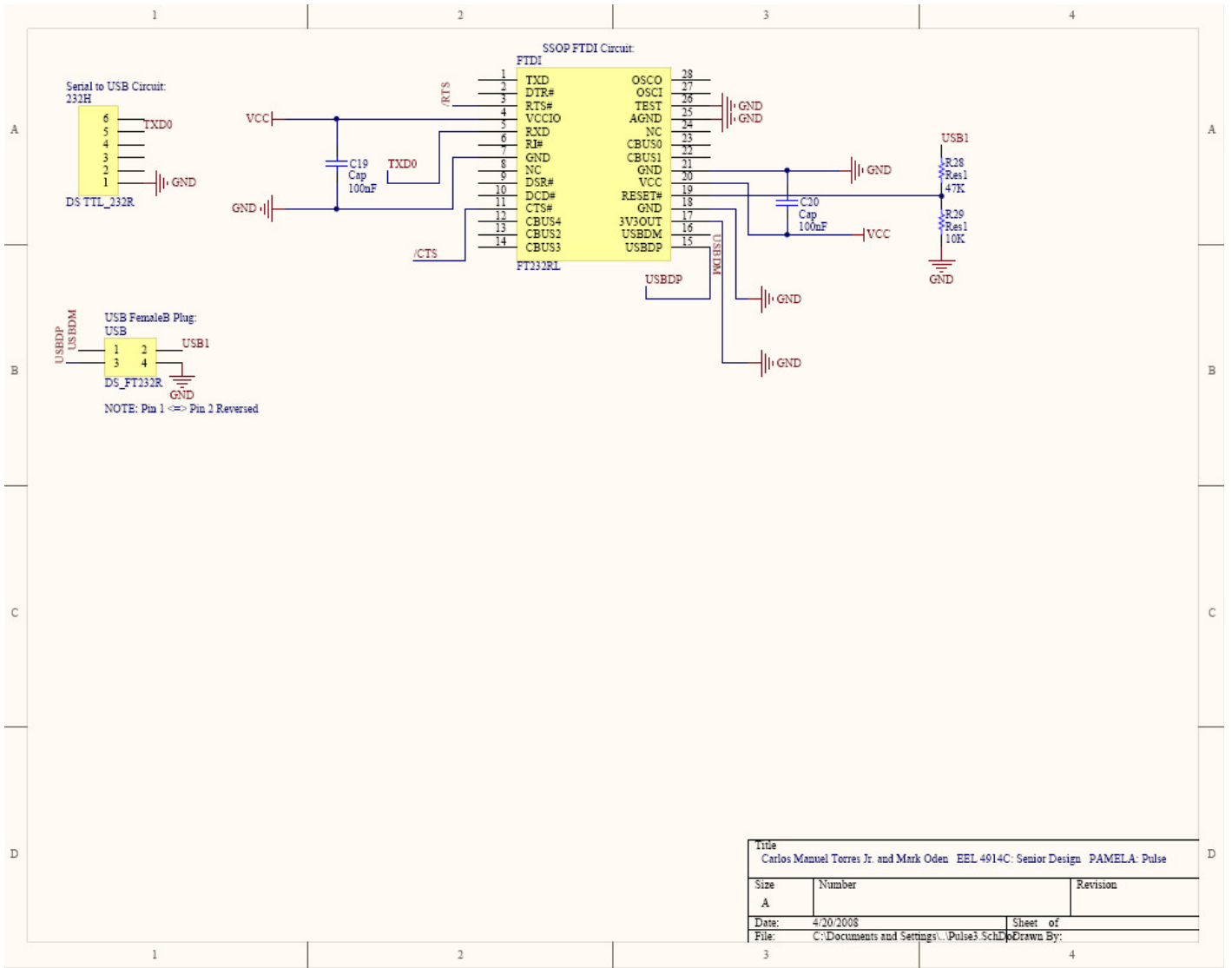
Appendix B. Circuit Design and Layout:



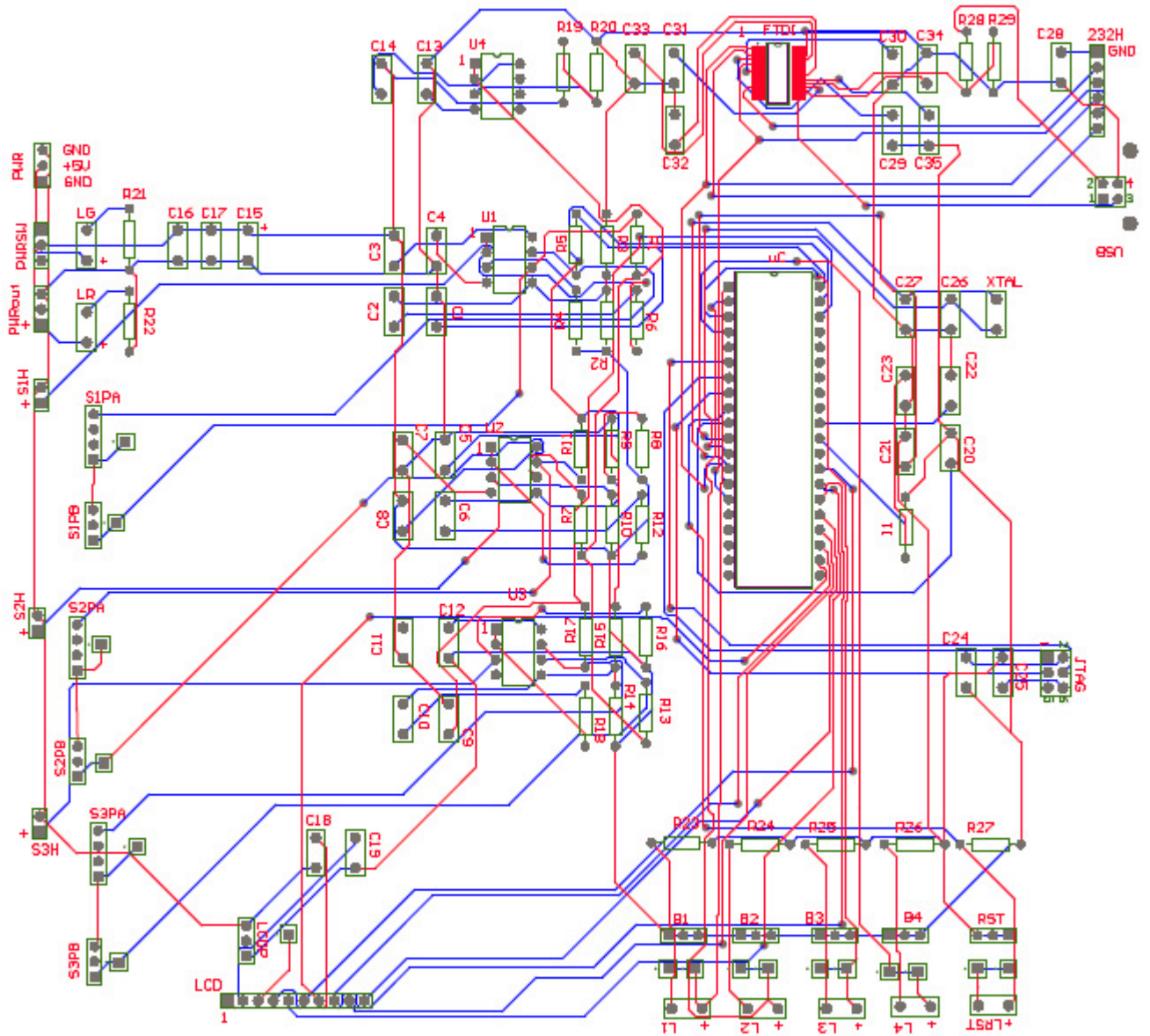
Amplification Circuits



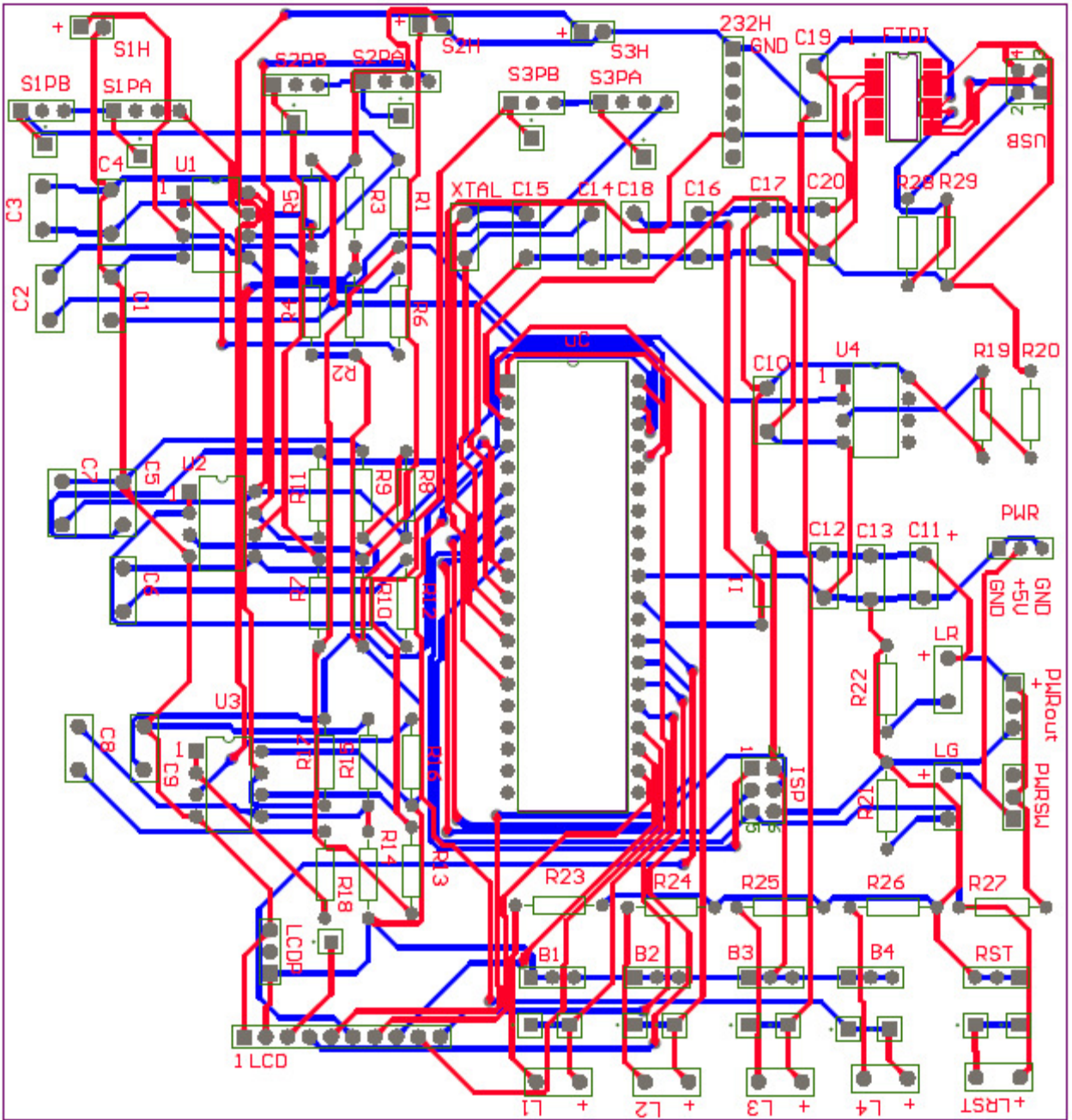
Microcontroller interconnects, power stabilization circuit, push button inputs



Serial-to-USB circuit design



Revision 1 Printed Circuit Board Design (7.5" x 7")



Revision 2 Printed Circuit Board Design (5" x 5")