MAE 3340 *INSTRUMENTATION SYSTEMS*

MAE 3340 Final Project Description, Spring 2015

Project Title: Design Study Comparing the Performance of Pulse Oximeter (Heart Rate Monitor) Prototypes Based on Competing Technologies.

Project Requirements:

Each MAE 3340 lab section will design, build, integrate and test prototype oximeter designs based on 1) photo-resistive, and 2) photo-diode technology. Each team will use the designs to evaluate team member resting pulse-rate and pulse-rate following vigorous activity (one round-trip up 4 flights of stairs in the ENGR building).

Project team will use appropriate statistical analysis methods to make projections for the USU Engineering student body with regard to the resting heart rate and heart rate following vigorous activity (maximum heart rate). These projections will be compared to the USA population at large.[1]

Project Deliverables:

Each laboratory section will work together as an integrated product team (IPT). Section 513, that only has 5 members re invited to recruit volunteers to use the developed devices and increase the size of their statistical data-base. Specific project deliverables are

1) Final Oral Briefing (*75 points*)
2) Final Written Report (*100 Points*)
3) Peer Review Surveys (*25 Points*)

Oral Briefing Requirements:

The oral reports will be presented during the last day of class, Friday *April 24, 2015 11:30-12:45 MDT*, and during the regularly scheduled final exam period, *Friday May 1, 9:30-11:20 a.m*. All presentations will be held in Fine Arts-Visual 150. *Attendance is Mandatory.* Please arrive on time. *Presentations will begin promptly at 11:35 on the 24th and 9:35 on May 1.*

Each group is encouraged to have at least two but no more than three oral presenters. Required elements of the presentation are listed below. All presentations will be developed using the presentation template linked on the MAE 3340 Web page. *Please use "YouTube" for linked video presentations. Do not embed videos in your briefing as these embedded files often "hang" the classroom computer. Missing required elements will result in a deduction of 5 points each from the final presentation score*.

1. Title Slide with Team Section, TA Name, Normal Meeting Time, and Team Name.
2. Organizational Chart Showing Team Members and Duty Assignments.
3. Background Theory and Concept of Operations for Each Device.
4. Functional Block Diagram of Each Device.
5. Software Description.
6. Example Time History Traces for Each Device.

7. Statistical Analysis of Results.
8. Lessons learned.
9. Conclusion

Each oral briefing will be 12 minutes long. Please time the briefing to allow 10 minutes of presentation, and 2 minutes of follow-up questions from the review panel. The presentation format is specifically up to each team's discretion, but slide layout should follow the template provided on the MAE 3340 web page. Presentations will be judged on the following elements.

Presentation Delivery
Student Roles Clearly Defined
Organizational Chart Clarity/Conciseness/Completeness
Technical Quality of the Presentation • *Effectiveness of Designs,* • *Completeness of Presented Results,* • *Clarity of Statistical Analysis*
Concluding Remarks and Project Summary
Responses to Questions from Review Panel

Report Requirements:

The final written report is due on May 1 at the beginning of the final oral review session. The final report will comply *rigorously* with the American Institute of Aeronautics and Astronautics (AIAA) report format.[2,3,4] The report must be highly referenced; using external information sources without complete citation will be considered as plagiarism and may cause the report to be disqualified (*the team will receive a score of zero*). The written report must contain the following elements listed below. Missing elements will be given a score of *"zero."*

1. Abstract. The abstract must be *exactly* 200 words in length. (5pts)
2. Table of Symbols. (5 pts)
3. Introductory section. (10 pts)
4. List of team members and organizational chart showing member roles within the project. (5 pts)
5. Discussion of background theory and measurement requirements. (10 pts)
6. Design schematics and analysis. (10 pts)
7. List of parts and components. (5 pts)
8. Assembly images. (5 pts)
9. Test and analysis section.
    a. Circuit(s) analyses. (5 pts)
    b. Software description (5 pts)
    c. Sample time history comparisons. (5 pts)
    d. Statistical Analysis of results (5 pts)
    e. Description of "lessons learned." (5 pts)
10. Conclusion. (10 pts)
11. Reference bibliography. References must comply with AIAA format. (5 pts)

12. Appendices, Component Spec Sheets, etc. (5 pts)

Peer Review Survey Requirements:

Each student will be asked to complete an anonymous on-line survey rating the effectiveness of the other members of the project team (including themselves). *Peer survey scores will count as 25% of the final oral briefing score.* **Laboratory sections where all students complete the on-line survey will receive an additional two points on their project score.** Each student will rate the other team members on the following questions:

1. Attendance at all lab sessions and required sub-team meetings. *(0 Low, 5 high)*
2. Attitude towards working with team unit. *(0 Low, 5 high)*
3. Reliability of delivering assigned tasks on time. *(0 Low, 5 high)*
4. Technical effectiveness of completing assigned tasks. *(0 Low, 5 high)*
5. Willingness to assist other team members in accomplishing assigned tasks. *(0 Low, 5 high)*
6. Overall contribution to team success. *(0 Low, 5 high)*

Background Information:

Pulse oximetry[5,6] is a non-invasive method for monitoring a patient's O_2 saturation. This photo-based technique measures the light absorption and refection properties of deoxygenated and oxygenated hemoglobin. The amount of light absorbed in the hemoglobin is calculated using the by the Lambert-Beer Law[7] that associates light absorption with the wavelength of the beam light, the path length, and the absorption coefficient of the blood constituents.

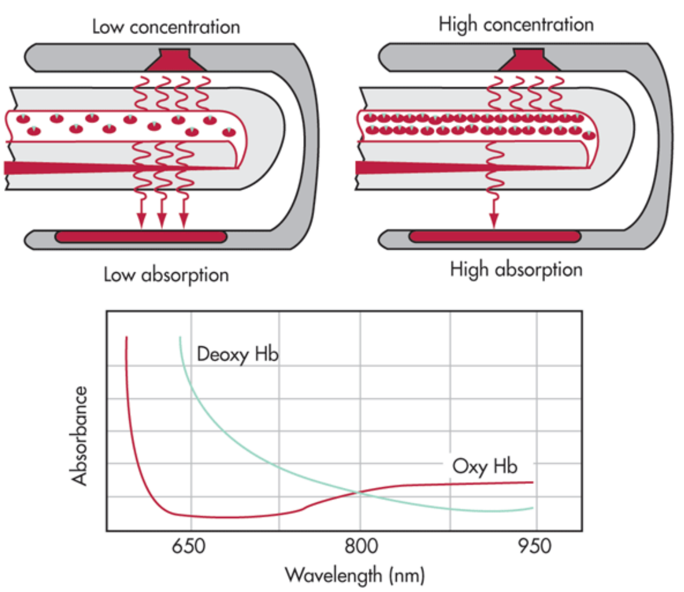


Figure 1. Fundamental Concept of Pulse Oximetry.

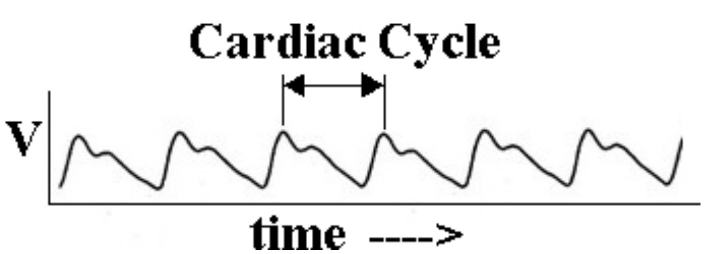


Figure 2. Voltage Profile for Typical Cardiac Cycles.

Pulse oximeters are being widely used for non-invasive, simultaneous assessment of hemoglobin oxygen saturation. They are reliable, accurate, relatively inexpensive and portable. Pulse oximeters are often used for estimating heart rate at rest and during exercise.

The majority of body tissue is nearly opaque to light with the majority of light is absorbed or reflected by our organs and tissues (skin, bone, muscle, blood). In extremities like fingers, toes, or ear lobes the tissue is semi-transparent and allows partial light transmission. Illuminating these tissues with Light Emitting Diodes (LEDs) and measuring the amount of light absorbed by the tissue using a light-sensitive component allows the concentration of oxygen in the arterial blood to be estimated. This technique is also sufficient to allow the test specimen's heart rate to be calculated.

Figure 1 shows the fundamental concept. The absorbance differences between oxygenated and deoxygenated blood is particularly large near visible light red wavelengths of 650 nm. Oxygenated hemoglobin absorbs more infrared light and allows more red light to pass through. Deoxygenated (or reduced) hemoglobin absorbs more red light and allows more infrared light to pass through. Red light lies in the 600-750 nm wavelength light band. Infrared light lies in the 850-1000 nm wavelength light band. Wavelengths of 660 nm and 910 nm are frequently used. Bright overhead lights may cause the oximeter to be inaccurate, similarly excessive patient motion may cause difficulties in picking up an adequate signal.

Transducer Circuit Concepts:

The basic transducer premise is to start with a light source and a light detector, placed on opposite sides of a translucent tissue area like a thumb or finger. The light source penetrates the tissue and impinges on the photo-detector, and the resulting signal is passed through a signal conditioning circuit to produce a sensible output voltage. The transducer output voltage will be proportional to the blood absorbance, and will read "high" during the Systolic cardiac cycle where the arteries are filled with the maximum blood level. The signal will read "Low" during the Diastolic cardiac cycle where blood returns through the veins and the blood pressure drops to a minimum level. Counting the frequencies of these high and low cycles can be used to estimate the pulse rate. Figure 2 shows the expected voltage profile for a typical series of cardiac cycles. The "Cardiac Cycle" represents one heartbeat. Figure 3 shows a typical mounting of the diode and photo-sensor on the "test digit."

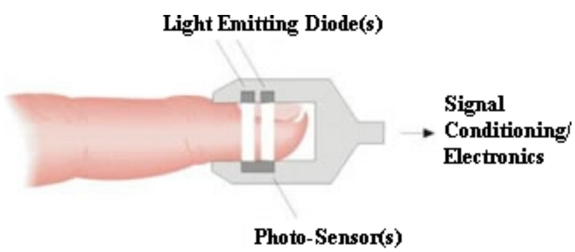


Figure 4. Pulse Oximeter Sensor.

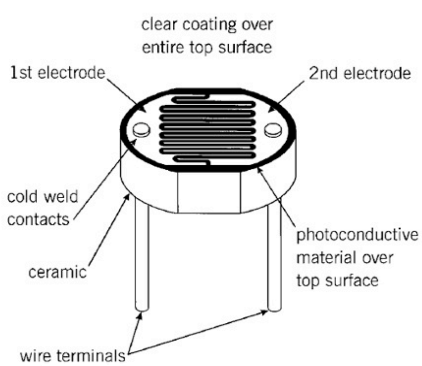


Figure 3. Typical Photo-Resistor Layout.

Photo-Resistive Sensing Circuit:

The first circuit concept to be investigated for the pulse oximeter transducer will use a photo-sensitive resistor.[8] Figure 4 shows a typical photo-resistor design. The resistance of this sensor varies widely depending on the level of light exposure. Typical sensors are made from CdS (Cadmium Sulfide), CdSe (Cadmium Selenide), and CdSSe (Cadmium Sulfide Selenide). CdS sensors are most commonly used.

To ensure maximum sensitivity, it is critical that the response of the resistor be well matched to the illuminating light source. A major advantage of CdS cells is that they present a spectral response that closely matches that of the human eye. Figure 5 shows a typical resistance profile as a function of the level of illumination, and the relative output sensitivity as a function of the illuminating light wavelength.

Figure 6 shows two potential circuit configurations that can be used to sense the change in resistance of the sensor as a function of the illumination level; 1) voltage divider, and 2) Wheatstone bridge. It is the responsibility of the design team to select the appropriate circuit, photo-resistor and matching components, and appropriate signal conditioning. The team is also responsible for ensuring that the wattage drawn by each component is within specified limits. If necessary the output from the photodiode circuit must be amplified.

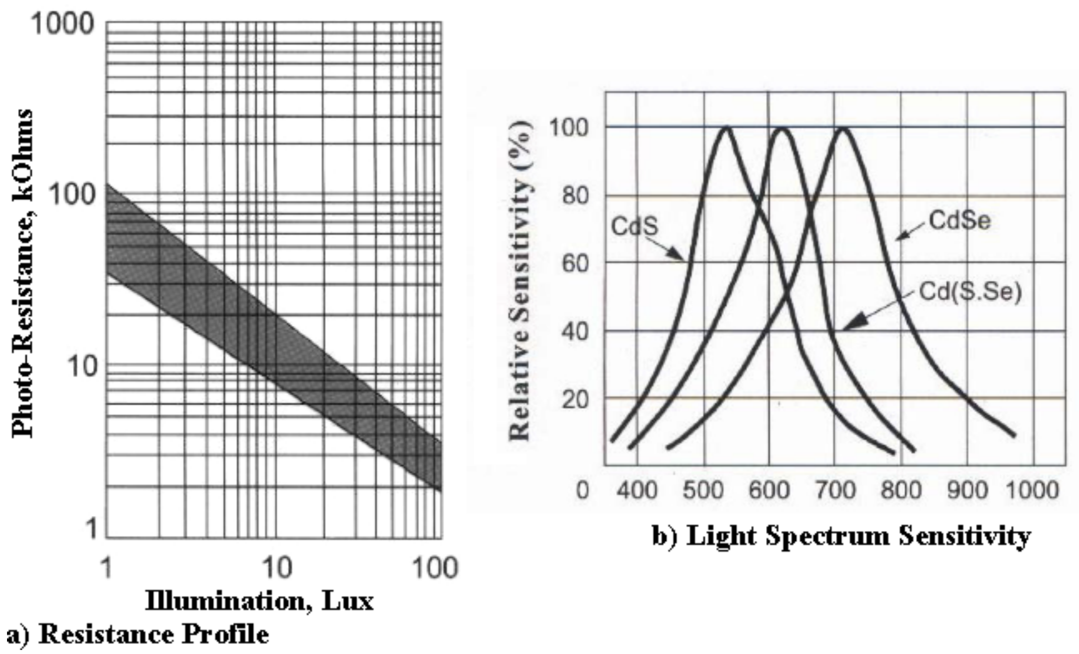


Figure 5. Typical Response Profile for CdS Photo-Resistor.

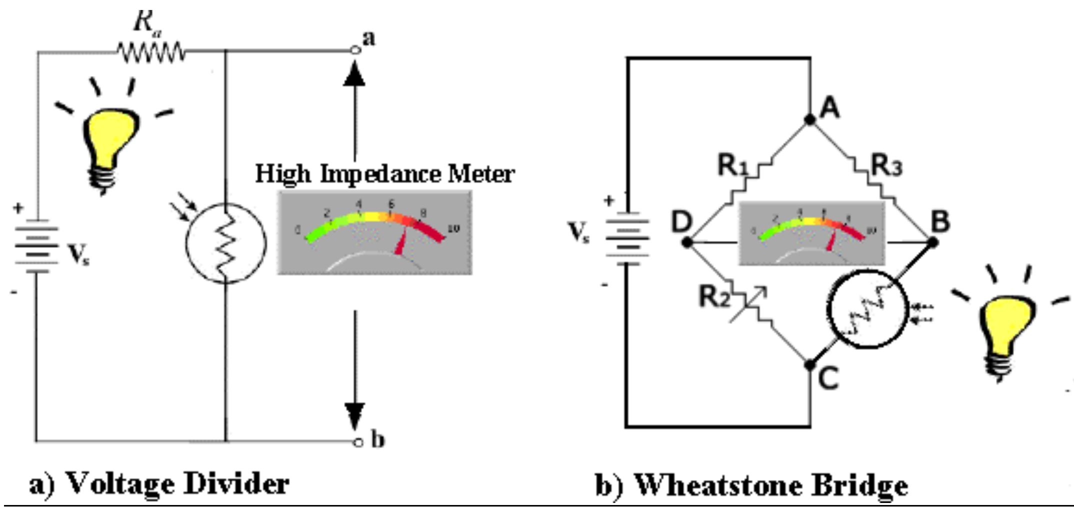


Figure 6. Circuit Options for Photo-Resistive Transducer.

Photo-Diode Sensing Circuit:

The second circuit concept to be investigated for the pulse oximeter transducer will use a photo-diode that produces an output current proportional to the illumination level.[9,10] When a photon of sufficient energy strikes the diode, the photon creates an electron-hole pair. This mechanism is also known as the inner photoelectric effect. If the absorption occurs in the junction's depletion region these carriers are swept from the junction by the built-in electric field of the depletion region. Thus holes move toward the anode, and electrons toward the cathode, and a photocurrent is produced. The produced current flows in the opposite direction to current in a normal diode or LED. These components are essentially single-element solar cells that output a small current proportional to the sensor illumination. Figure 7 shows the fundamental working principle for a typical photodiode

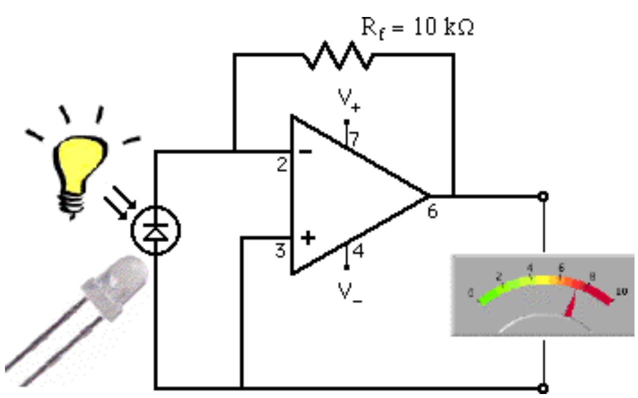


Figure 7. Transimpedance Amplifier for Photo-Diode.

A transimpedance amplifier[11] is an easy way to convert the photodiode current to a voltage output but still keep the voltage drop across the at zero. Figure 7 shows a typical arrangement for this amplifier circuit. When light hits the photodiode the generated current flows through R_f to the output terminal of the OpAmp. The resulting output is negative relative to ground. Because no current flows into the op-amp, the voltage drop across photo-diode is zero. With this arrangement OpAmp output voltage vs. incident light can be linear over 5-10 orders of magnitude of illumination input.

Figure 8 shows a typical current output as a function of illumination, and the spectral response of the sensor as a function of the input light wavelength (Ref. 9). Note that the produced current is very small and must be amplified to produce a useable signal. Figure 7 shows the short-circuit current output from the sensor (zero voltage drop across the diode). As the voltage drop across the diode increases the linearity of the sensor response decreases significantly.

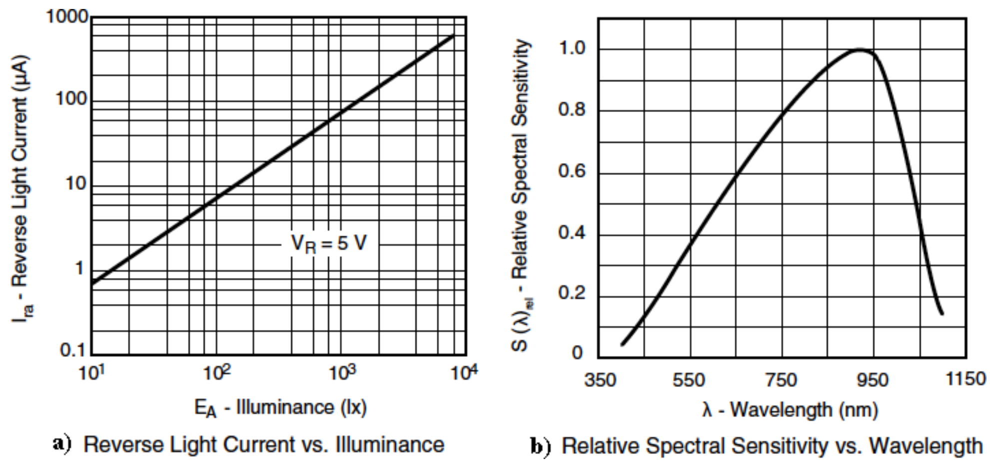


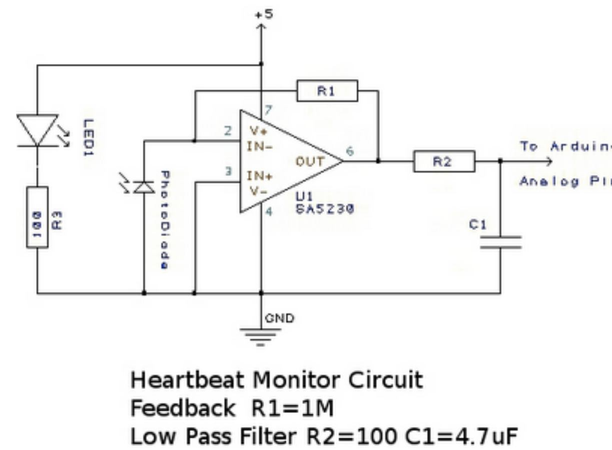
Figure 8. Typical Photo-Diode Short Circuit Current Response and Output Spectrum.

As with the photo-resistive circuit design, it is critical that the response of the photo-diode be well matched to the illuminating light source to ensure maximum sensitivity. It is the responsibility of the design team to select the appropriate photo-diode and matching components, and appropriate signal conditioning to allow this circuit to operate properly, and to ensure that the wattage drawn by each component is within specified limits.

This circuit is a bit more "cantankerous" than the photo-resistive circuit and generally higher quality components including the op-amp are required. *World Famous Electronics llc*, recommend the following components[12]:

- *Operational Amplifier: SA5230 Op Amp from ON Semi.*
- *Alternate: Texas Instrument OPA177.*
- *Photodiode: Osram SFH 203 P.*
- *LED: is Everlight EL-IR204-A, peak wavelength at 940nm.*

Figure 9 shows their circuit design. The series resistor and parallel capacitor across the output has the effect of removing high frequency noise from the measured signal (LOWPASS FILTER).



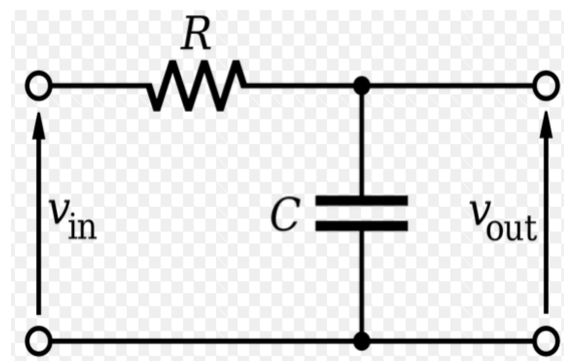


Figure 9. Transimpedance Amplifier with Integrated Lowpass Filter on Output Terminal.

Figure 10. Example LED Power Circuit.

Background on Light Emitting Diodes (LEDs):

The intensity of light that a LED produces is directly proportional to the current drawn. A resistor in series can be used to set this current. For example, as shown by Figure 10, at *10mA* the voltage across the LED drops about 2.05V. With a 5V supply, this leaves 3V drop across the resistor. Therefore, setting *R = 300Ω will give a 10 mA current draw*.

Different color LED's drop different voltages (Red 1.7-2.5V, yellow 2.0-2.3V, green 2.0-2.6V, blue & white 3.1-3.7V). The LED voltage drop increases slightly with increasing current. The LED's lifetime varies exponentially with current. The LED may last 100,000 hours at 5mA, 10,000 hours at 20mA, and 100 hours at 100mA. *The reverse voltage is very low (sometimes only a few volts) so don't put the LED in backwards*. For this project you don't need to know the exact voltage drop of the diode. If it's not bright enough, lower the current limiting resistor. The maximum DC current should be listed on the LED data sheet. Allow sufficient margin so as to not burn up the LED.

Software:

The NI MyDAQ unit will be used to acquire the output date from each circuit, and it will be necessary to configure the LabVIEW software to properly acquire, process, and display the data. A sample template for this software is available online at the MAE 3340 Web page. Figure 11 shows the front panel display. Displayed are the time history of the acquired data and the Fourier spectrum where the root sum squares of the Fourier coefficients are plotted as a function of frequency.

$$\sqrt{A_f^2 + B_f^2} \rightarrow vs. \rightarrow frequency$$

Notice that the time history plot shows two data traces, the white data trace is the raw sensed transducer output voltage, and the red trace is a processed version of the time history plot. This process trace has been "band-pass" filtered using the Fourier transformation. The raw signal is expanded into a Fourier series, and then all Fourier coefficients below 0.5 Hz and above 5 Hz are set to zero. The red line on the time history graph shows the series response that results with these frequencies removed. This signal processing "trick" is a key element of the algorithm. Because of the low magnitude of the detected signal, there exists a significant potential for noise contamination, especially at frequencies that are outside of the physiological frequency of interest. Figure 12 shows two examples of these contamination sources. Here the DC-level of the signal wanders significantly, and even small motions can introduce contamination into the signal. Notice that the front panel also shows an "AC couple" button. Pushing this button sets the "A_0" Fourier coefficient to zero. What is the effect of this action on the signal? Why would one want to perform this action?

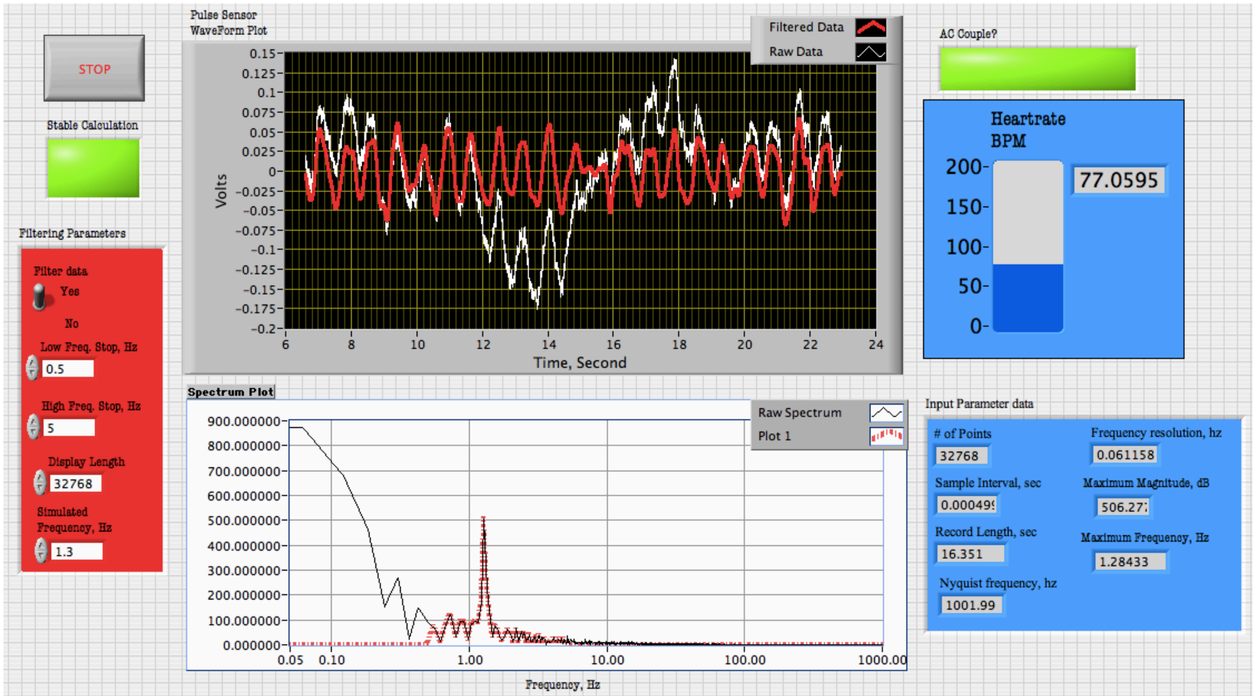


Figure 11. Front Panel of the Heart Beat Detection Software.

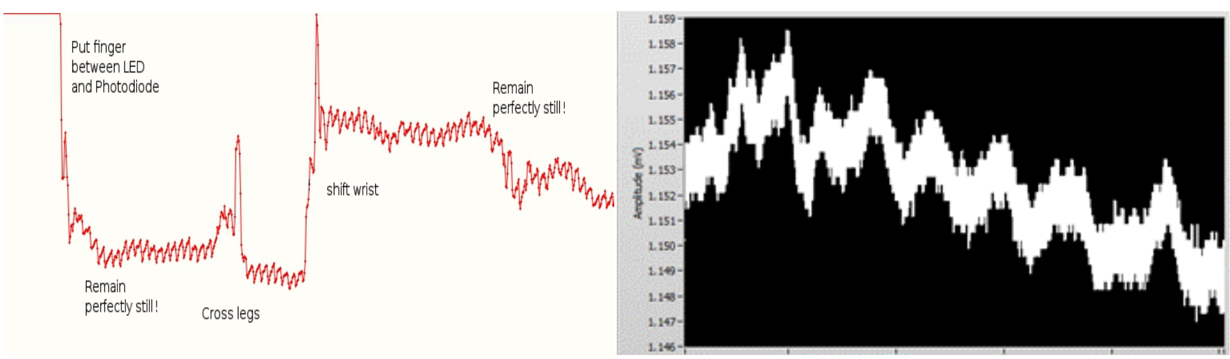


Figure 12. Example Noisy Signals Showing DC-drift and High Frequency Noise.

The minimum expected human heart beat -- even for a very fit person -- is approximately 50 beats per minute, and the maximum expected heart rate -- even after very vigorous exercise -- is approximately 240 beats per minute. Thus the expected signal frequency range of interest will vary from approximately 0.5 to 4.0 hertz (cycles/second), and is centered on approximately 2 Hz. Thus the selected "pass band" range is chosen to remove any spurious noise from the data. The very sharp spike on the filtered spectrum plot (red trace) corresponds to the pulse rate signal, and is easily detected by selecting the frequency corresponding to the peak spectrum value.

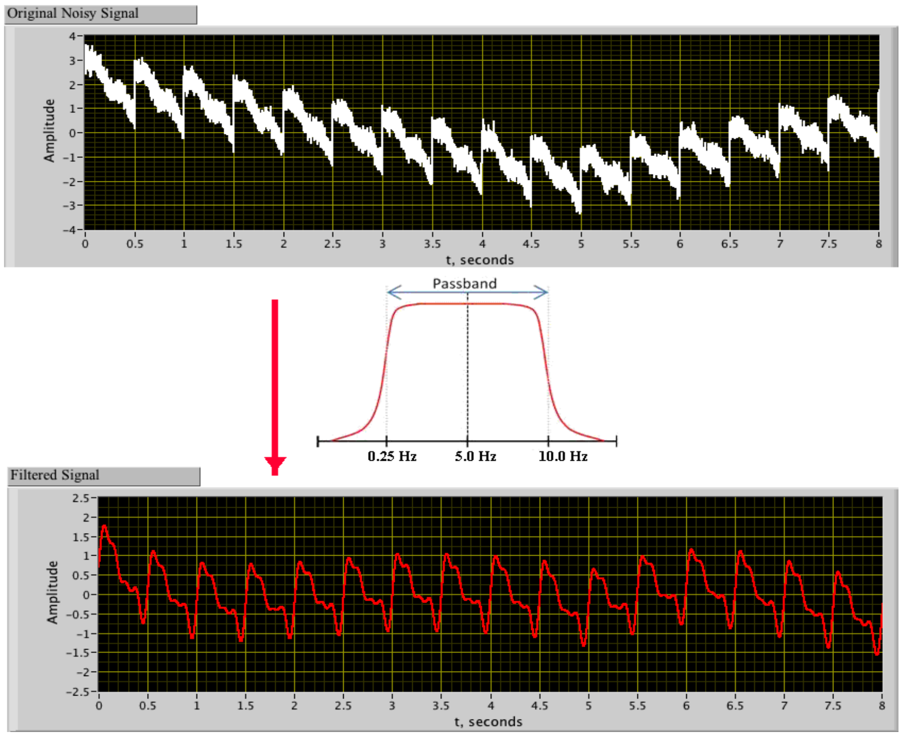
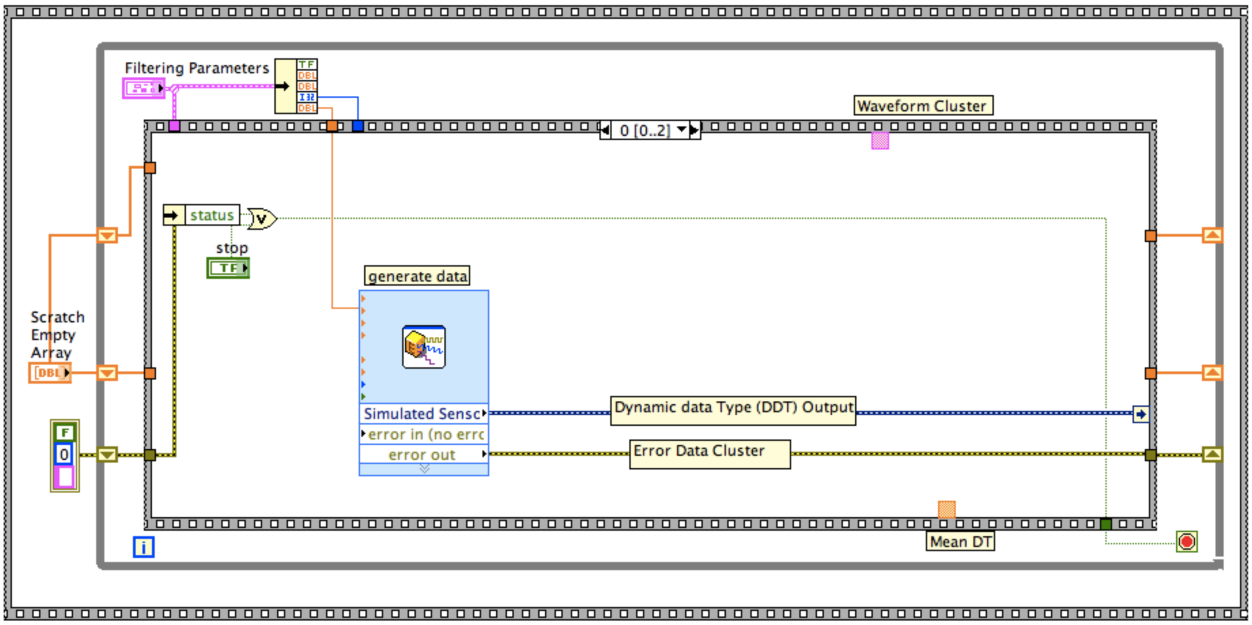


Figure 13. Pass-Band Processed Heartbeat Signal.

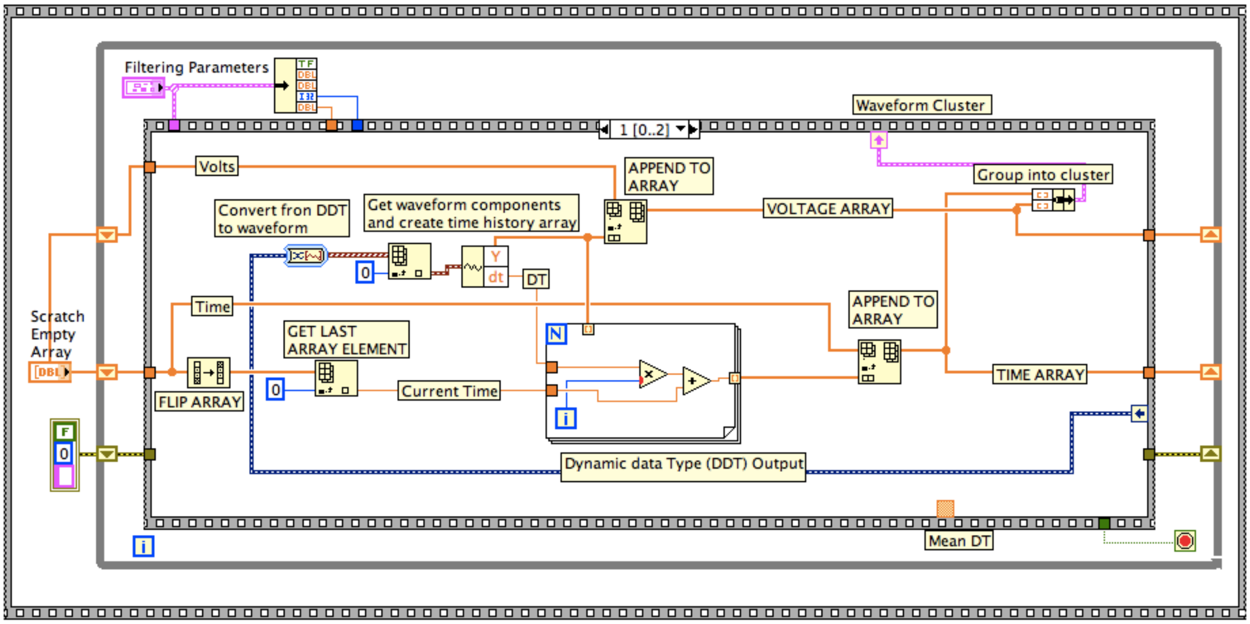
Figure 13 shows what happens when we measure a noisy signal, but we exclude frequencies that are not of interest; a filter of this form is known as a pass band-filter. The processed signal is derived from the original signal; except now all frequencies below 0.25 Hz, and above 10 Hz have been removed from the signal. Now the visibility of key features of the heartbeat signal is clearly enhanced. You will have to "play" with the filter block settings to get the best response from your system software.

The block diagram for the software contains three essential case-structure blocks inside of a while loop. This loop is performed continuously as long as the "stop button" on the front panel has not been pushed, and there is not read error on the data acquisition system. These essential blocks are shown on Figures 14 (a) through (c). Block (a) acquires the data from the MyDAQ device. As shown this block merely simulates the heart-beat signal. It is the student design team's responsibility to replace this block with an appropriate DAQmx block at acquires the data. Data should be acquired as a rate that is sufficient to capture the desired frequencies; also sufficient data should be acquired to allow the pulse frequency to be resolved.



(a) Data Acquisition Block

Currently, as shown by Figure 16, the simulation block is set to dump a simulated output signal at a rate of 2000 samples per second, and a length of 500 samples. These values correspond to a Nyquist frequency of f_n=1000 Hz, and a record length of $T=0.25$ seconds. This record length corresponds to a frequency bandwidth resolution of only 4 Hz. Thus, a longer record length is required to resolve the pulse rate. Block (b) takes the data returned by DAQmx and converts it to a normal floating point data vector. The data are appended to a storage array so that a sufficient number of points can be accumulated to allow the desired pulse frequency to be resolved. Thus block also builds up the time tag vector that corresponds to the time each voltage in the VOLTAGE ARRAY was acquired. The appended vector stores all of the data collected as long as the *while-loop* is running.

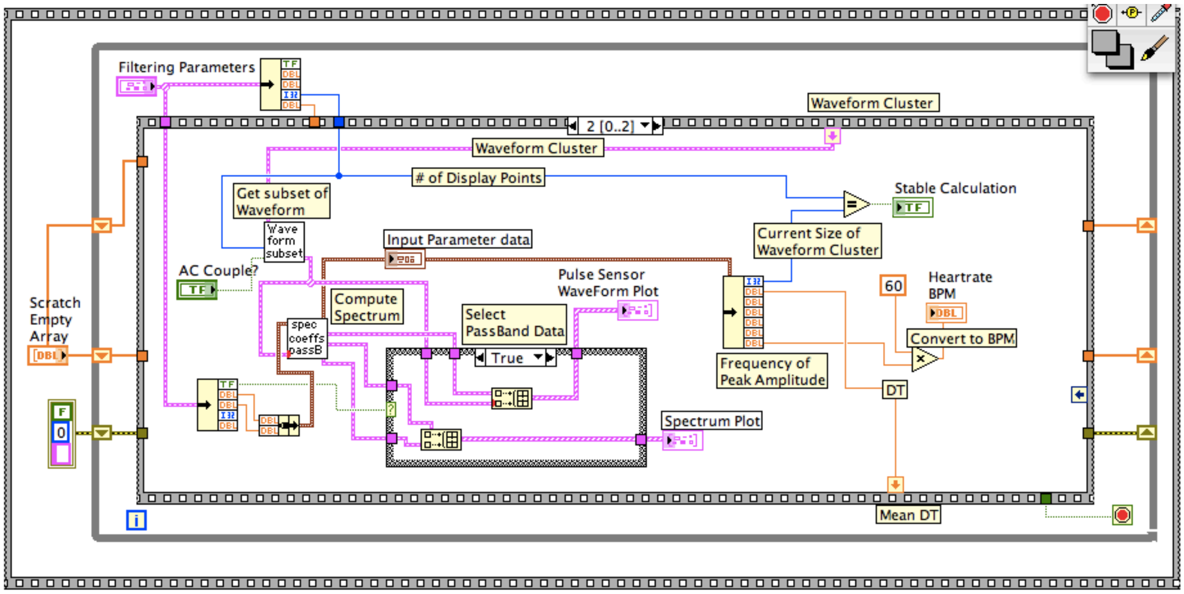


(b) Data Manipulation and Appending Block

Figure 14. Block Diagram of Heart rate Monitor Software.

Block (c) performs the Fourier Analysis and calculates the pulse rate. This first block selects a subset of the total appended data array and keeps the last N elements of the data vector. The value of N is selectable from the "Display Length" parameter of the front panel. Thus for this example where N=32,768, and the sample rate is 2000 sps, the record length to be analyzed is T = 32,768/2000 = 16.384 seconds. This length corresponds to a frequency bandwidth resolution of 0.06 Hz, and should be sufficient to resolve the desired heart rate. This data buffer is passed to the Fourier transform routines *(spec coeffs passB)* along with the desired pass band frequencies to calculate the raw and band-passed Fourier Coefficients and Fourier series. The filtered signals are over plotted against the raw signals. The frequency corresponding to the maximum coefficient magnitude is selected as the heart rate frequency.

Figure 15 shows the block diagram of the Fourier Analysis Routine. This routine uses the labview FFT numerical algorithm to calculate the raw Fourier spectrum coefficients, zeroes-out the *"A"* and *"B"* coefficients frequencies outside of the pass-band, and uses the Fourier series to reconstruct the filtered time history signal. The frequency corresponding to the Fourier Coefficients with the maximum magnitude -- $(A^2 + B^2)^{1/2}$ -- is selected as the heart rate value. This criterion relies on the fact that the sensed heart rate monitor signal should have a dominant frequency at the heart rate of the patient.



(c) Signal Processing Block

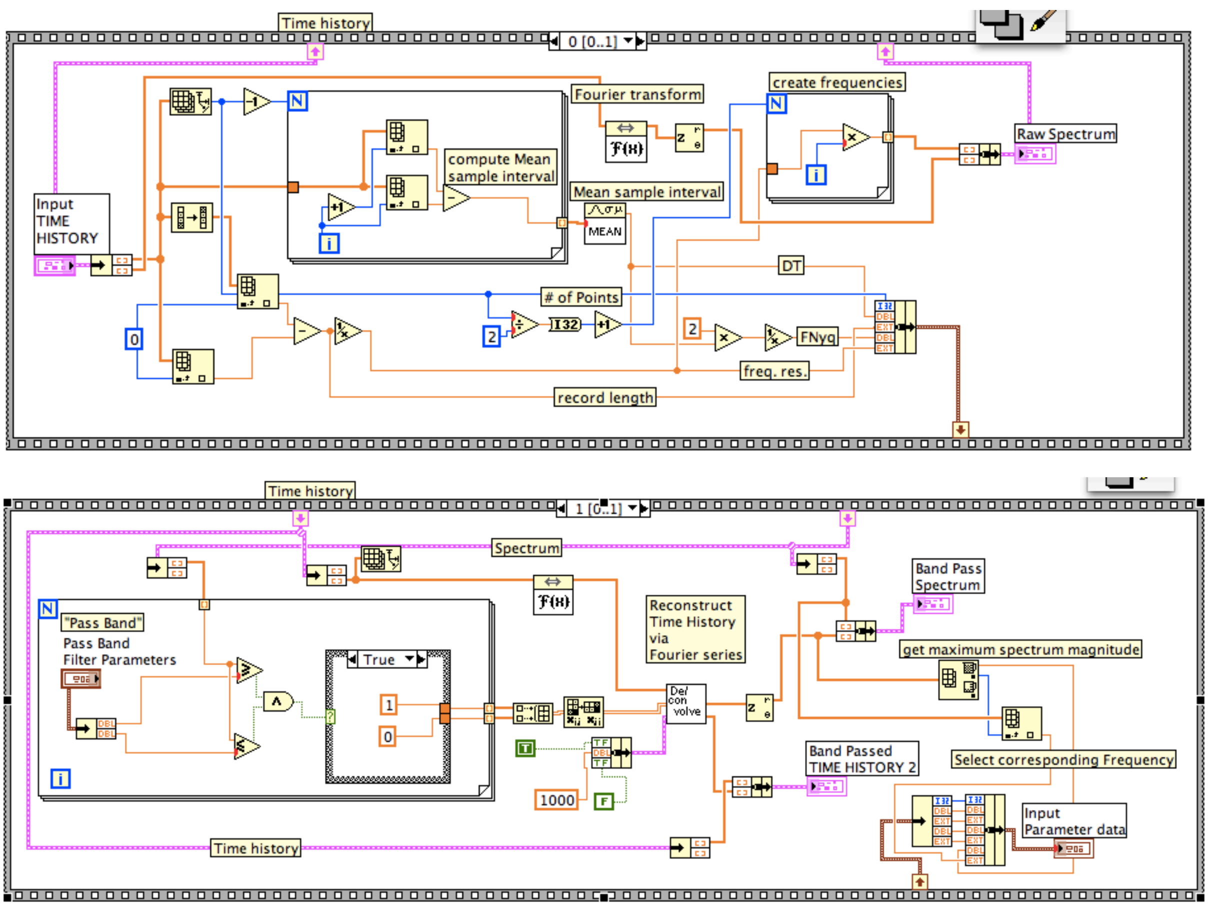


Figure 15. Fourier Transform and Bandpass Filtering Blocks.

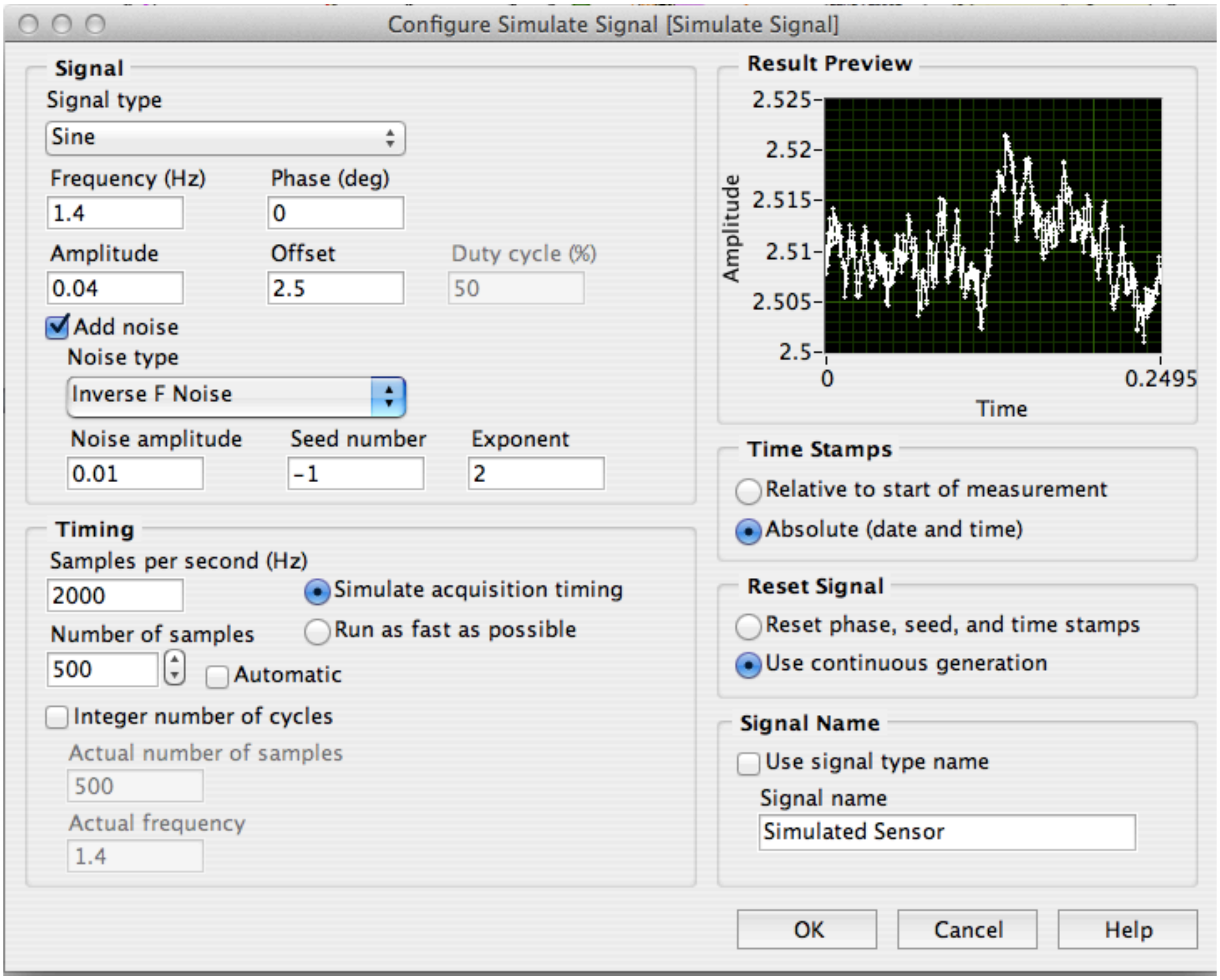


Figure 16. Front Panel of Signal Simulation Block.

As stated previously, the shown Block (A) merely simulated the heart rate signal. Figure 16 shows the front panel of this simulation block. This element generates the simulated signal with a main central frequency, and then contaminates the signal with spurious noise. ***It is the student design team's responsibility to replace this block with an appropriate DAQmx block at acquires the data. Data should be acquired as a rate that is sufficient to capture the desired frequencies; also sufficient data should be acquired to allow the pulse frequency to be resolved. You must show this calculation in your final report.*** Using NI "DAQ Assistant" to replace this block with an appropriately con figured DAQmx block is the student team's responsibility. See the lab 8 lecture notes for a review of this process. As shwn by Figure 16, *be sure to configure your DAQmx block to acquire "N samples" at an appropriate sample rate. Also, depending on your device signal connections, set the channel for either single-ended or differential acquisition*. For more information please see the DAQ assistant tutorial at "http://www.ni.com/tutorial/4656/en."

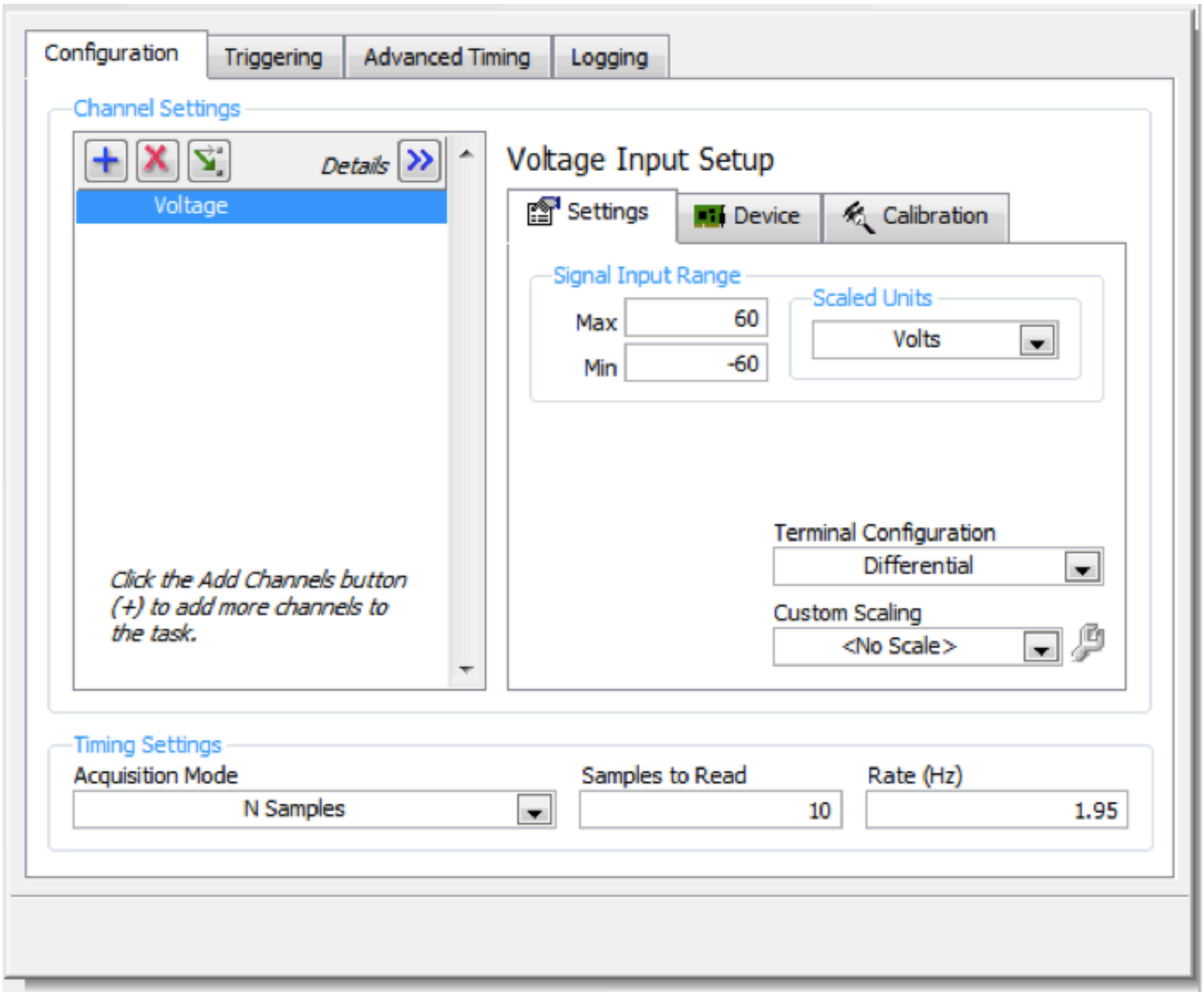


Figure 16. DAQ Assistant DAQmx Setup Panel.

References.

[1] Weil, R., and Stoppler, M. C., " How do I calculate my target heart rate during aerobic exercise?," *http://www.medicinenet.com/aerobic_exercise/page6.htm*, [Retrieved 30 March 2014].

[2] Anon, "AIAA Tech Papers Style Guide," *https://www.aiaa.org/uploadedFiles/Events/Related_Content/Author_and_Organizer_Resources/Author_Resources/AIAAStylePreferences.doc*, [Retrieved 30 March 2014].

[3] Anon., AIAA Paper Template (MS Word), *https://www.aiaa.org/uploadedFiles/Events/Related_Content/Author_and_Organizer_Resources/Author_Resources/Preparation%20of%20Papers%20for%20AIAA%20Technical%20Conferences.doc*, [Retrieved 30 March 2014].

[4] Anon., Latex Template, https://www.aiaa.org/WorkArea/DownloadAsset.aspx?id=4199, [Retrieved 30 March 2014].

[5] Millikan G. A. (1942). "The oximeter: an instrument for measuring continuously oxygen-saturation of arterial blood in man". *Rev. Sci. Instrum* **13** (10): 434–444. doi:10.1063/1.1769941

[6] Torres, D., "Build A Wrist Heart-Rate Monitor Using An Ultra-Low-Power MCU," *Electronic Design*, *http://electronicdesign.com/digital-ics/build-wrist-heart-rate-monitor-using-ultra-low-power-mcu*, [Retrieved 30 March 2014].

[7] Tissue, B. M., "Beer-Lambert Lwe," *http://www.files.chem.vt.edu/chem-ed/spec/beerslaw.html*, [Retrieved 30 March 2014].

[8] Anon, "CdS Photoconductive Cell, GL5528," *http://dlnmh9ip6v2uc.cloudfront.net/datasheets/Sensors/LightImaging/SEN-09088.pdf,* [Retrieved 30 March 2014].

[9] Anon, "Silicon PIN Photodiode, BPW34, BPW34S," Vishay Document Number: 91000, Revision: 18-Jul-08 *https://www.sparkfun.com/datasheets/Prototyping/Solar/bpw34.pdf,* [Retrieved 30 March 2014].

[10] Anon, "Silicon PIN Photodiode, BPV10F," Vishay Document Number: 91000, Revision: 02-Oct-12 *www.vishay.com/docs/81503/bp10nf.pdf*, [Retrieved 30 March 2014].

[11] D'Donnell, W., "Things You Should Kmnow about LED's and Photodiodes," *http://www.physics.unlv.edu/~bill/PHYS483/LED_PIN.pdf*, [Retrieved 30 March 2014].

[12] Anon., *http://pulsesensor.com/blogs/news/6326816-anatomy-of-the-diy-heart-rate-monitor, pdf,* [Retrieved 03 April 2015].