Pulse Monitor and Oximetry

BE/EE/MedE 189 a

1 Background

A pulse oximeter measures the oxygen saturation of the blood and changes in blood volume in the tissue by measuring the plethysmograph signal. The device is based on two physical principles: (1) the presence of a pulsatile signal generated by arterial blood; (2) the fast that oxyhemoglobin (O_2Hb) and reduced hemoglobin (Hb) have different optical absorption spectra. You can read the attached paper by Tremper and Barker to familiarize yourselves with the principles of pulse oximetry.

Pulse oximeters are used in many monitoring and diagnostic applications. Of particular interest is data acquisition of beat intervals. Surprisingly, in a healthy individual, the intervals between successive heartbeats vary in a rather chaotic manner. It has been reported that patients with congestive heart failure (CHF) have decreased cardiac chaos as compared to healthy individuals (see the attached paper by Poon and Merrill, especially Fig. 1). CHF patients are found to have similar chaotic heartbeat interval except "frequently interrupted by periods of seemingly non-chaotic fluctuations." Thus, a frequency spectrum (obtainable by FFT) will not sufficiently reveal these periods of regular heartbeat intervals (refer to Fig. 1c of Poon and Merrill). Calculations of beat intervals directly can enable quantification of regularity of inter-beat times. You will use your pulse oximeter to make these measurements and quantify this regularity.

2 Specification

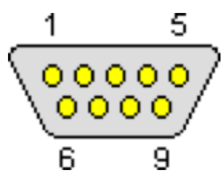
Your task is to construct a pulse oximeter using the commercial Nellcor Oxisensor II D25 oxygen sensor. Develop LabVIEW code to process the signal and display the pulse rate and oxygen level. Your instrument should thus be able to detect and display pulse and oxygen content information in real time. Your LabVIEW interface should also provide/allow for the following.

- Storing of data for later processing.
- Display of oxygen content, pulse, and DC signals.
- Measurement and characterization of inter-pulse times.
- Calculation and display of oxygen saturation (see the prelab questons for definition).

You are advised to first build a functioning instrument that can detect pulse and process the signal. Then, add the oxygen-sensing capabilities.

2.1 Circuit for the Nellcor sensor

The Nellcor Oxisensor uses a DB9 connector (refer to Fig. 1 for pinout information). It can be directly connected to the ELVIS II breadboard and can be attached to a finger, as shown in Fig. 2. The oxisensor consists of a red LED, an infrared (IR) LED, and a photodiode to measure light signal from both LEDs. The red LED is used for pulse measurement and the IR LED for oxygen content measurement.



Pin	Purpose
1	-
2	LED1
3	LED2
4	-
5	Photodiode a
6	-
7	Shield
8	-
9	Photodiode cathode

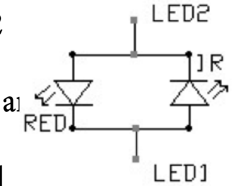


Figure 1: Nellcor Oxisensor II DB9 connector Pinout

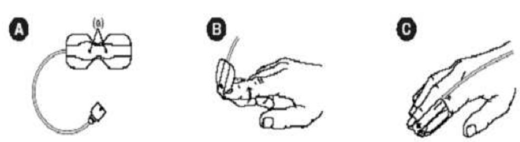


Figure 2: How to apply probe

Circuits for driving the red LED and the photodiode are shown in Fig. 3.

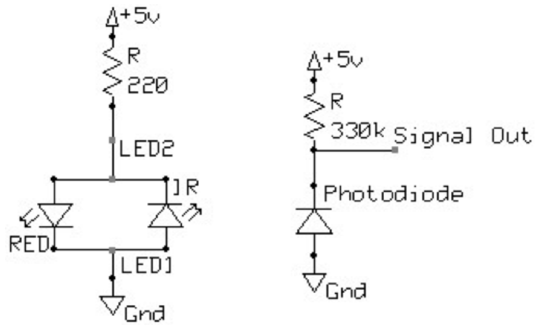


Figure 3: Circuits for driving the red LED and the photodiode.

When looking at the signal using a virtual oscilloscope in LabVIEW, you will notice that the signal is very weak; hence the need for filtering and amplification.

2.2 Filter and amplification circuit

Use the circuit shown in Fig. 4, or any related circuit that you want, to filter and amplify the signal. You will need to build two filter and amplification circuits, one for pulse detection, and one for detection of oxygen content. Please see the attached data sheet for the pin definitions for the LF442 op amp. (Note that you can also use an LF412 op amp, which has the same pin definitions and similar specs.) Your pulse signal should look similar to that shown in Fig. 5.

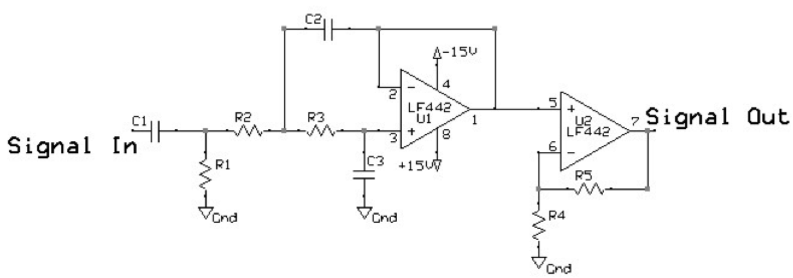


Figure 4: Filter and amplifier circuit. In the above circuit, you can try R1 = 150 kΩ, R2 = R3 = 1.8 MΩ, R4 = 10 kΩ, R5 = 1 MΩ, C1 = 2.2 μF, C2 = 0.027 μF, and C3 = 0.012 μF.

Note that resistors have no polarity so you can wire them up in any direction. Some capacitors have polarity, especially the high capacitance ones. The longer lead on the capacitor is the positive end—make sure you wire the capacitor such that the positive end faces the side of the circuit that is predominantly at a higher potential.

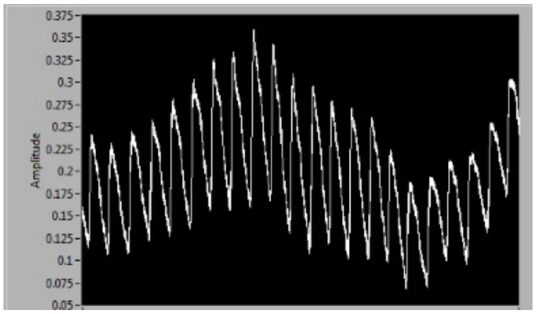


Figure 5: Example pluse signal

2.3 Measuring the pulse and oxygen content concurrently

To measure both the pulse and oxygen content concurrently, you need to turn on the red and the IR LED alternately and measure the pulse signal from both LEDs simultaneously. The block diagram of the pulse oximeter is shown in Fig. 6.

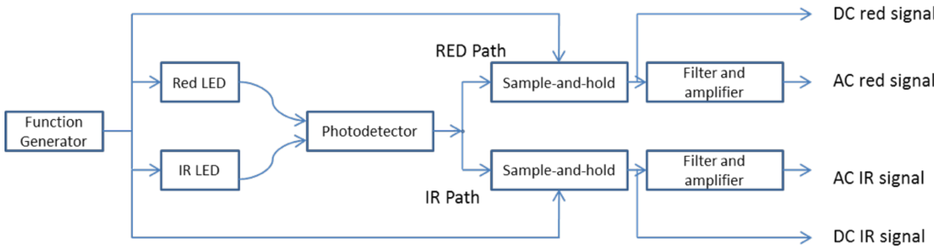


Figure 6: Block diagram of the pulse oximeter.

Use the circuit shown in Fig. 7a for driving the two LEDs. The "Signal In" in Fig. 7a is a square wave signal shown in Fig. 7b, which can be generated using the virtual function generator of ELVIS II. You should carefully consider what frequency to use for the square wave. Note that you will be able to see the flashing of the red LED, but not the IR LED, since you cannot see infrared light.

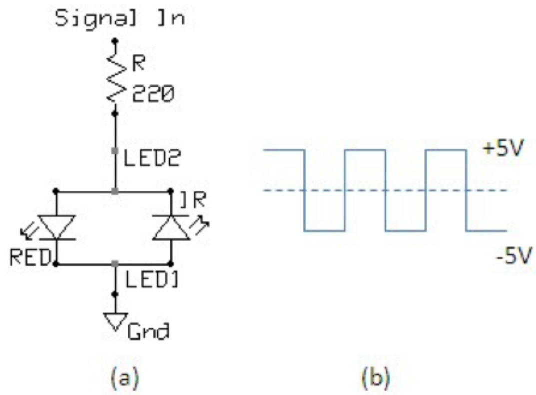
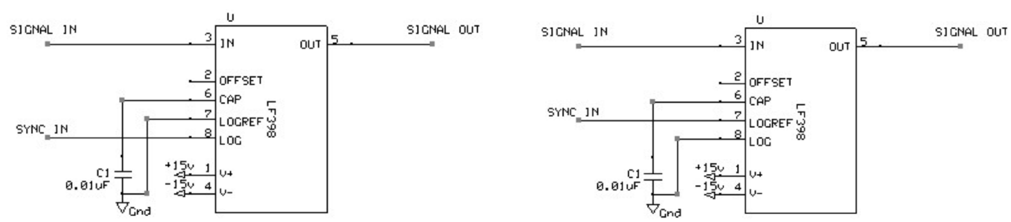


Figure 7: Circuit for driving the two LEDs

2.4 Sample-and-hold circuit

Use the LF398 for sample-and-hold. Refer to its specification sheet for details. Note the pin numbers in (a) and (b). The circuit is shown in Fig. 8, where Fig. 8a is for the RED path and Fig. 8b is for the IR path. Note that the only difference between the two circuits is the logic for sample-and-hold. The "SYNC IN" should be connected to the square wave in Fig. 7b directly.



(a) red path (b) IR path

Figure 8: Sample-and-hold circuits

3 Prelab questions

1. The basic physical principle of oximeter is the Beer-Lambert Law, which describes the absorption of a uniform medium when light is transmitted through it. The law can be written as

$$I = I_0 \mathrm{e}^{-\epsilon(\lambda)\cdot C\cdot D}, \tag{3.1}$$

where I is the transmitted light intensity, I_0 is the incident light intensity, $\epsilon(\lambda)$ is the extinction coefficient (also known as an attenuation coefficient or absorptivity) of the substance at wavelength λ, C is the concentration of the absorber in the medium, and D is the thickness of the medium. Defining optical density (OD) as the negative common logarithm (i.e. base 10) of the ratio of transmitted light to incident light, write the equation for OD. How are optical density and the medium thickness related?

2. There are numerous absorptive (and scattering) factors that contribute the attenuation of light through tissue. These various contributions add to the exponent term of Eq. 3.1:

$$I = I_0 \mathrm{e}^{-\sum_i \epsilon_i(\lambda)\cdot C_i \cdot D} \tag{3.2}$$

where i denotes the i^{th} absorptive component in the tissue. Suppose that $\epsilon_i(\lambda)$ is a different known function for each of these components and that there are 10 such components, how would you go about measuring C_i? Is it possible to find C_{10} by making just two measurements?

3. Suppose we know that concentration of the 10^{th} component oscillates between 0 and its full value C_{10}, would you be able to determine C_{10} by making just two measurements at a single wavelength? How? You may assume that you know the times when the concentration of the 10^{th} component reaches its respective minimal and maximal values. Why is this assumption necessary?

4. Suppose we know that concentrations of the 9^{th} and the 10^{th} components oscillate between 0 and their respective full values, C_9 and C_{10}. Their oscillations are exactly synchronized to each other. Is it possible to determine C_9 and C_{10} by making N measurements at only one wavelength ($N =$ any integer)? If not, what about making M measurements at two wavelengths? What is the minimum M? You may assume that you know when the concentrations of the 9^{th} and the 10^{th} components are minimal and maximal.

5. The pulse oximeter looks at how the transmission signal changes at two different wavelengths to determine the concentration of oxygenated and deoxygenated hemoglobin in arterial blood.

$$\begin{aligned} I(\lambda_1, \text{on}) &= I_{\text{DC}}(\lambda_1) + I_{\text{AC}}(\lambda_1) \\ &= I_{\text{DC}}(\lambda_1)\mathrm{e}^{-\left[\epsilon_{\text{O}_2\text{Hb}}(\lambda_1)C_{\text{O}_2\text{Hb}} + \epsilon_{\text{Hb}}(\lambda_1)C_{\text{Hb}}\right]D}, \end{aligned} \tag{3.3}$$

$$\begin{aligned} I(\lambda_2, \text{on}) &= I_{\text{DC}}(\lambda_2) + I_{\text{AC}}(\lambda_2) \\ &= I_{\text{DC}}(\lambda_2)\mathrm{e}^{-\left[\epsilon_{\text{O}_2\text{Hb}}(\lambda_2)C_{\text{O}_2\text{Hb}} + \epsilon_{\text{Hb}}(\lambda_2)C_{\text{Hb}}\right]D}, \end{aligned} \tag{3.4}$$

$$I(\lambda_1, \text{off}) = I_{\text{DC}}(\lambda_1), \tag{3.5}$$

$$I(\lambda_2, \text{off}) = I_{\text{DC}}(\lambda_2) \tag{3.6}$$

In these equations, the subscript DC refers to the baseline signal and the subscript AC refers to the pulsatile signal. Here, on and off refer respectively to the peaks and valleys of the pulsatile signal. According to the above equations, calculate the oxygen saturation, which is defined as

$$\mathrm{SaO_2} = \frac{C_{\mathrm{O_2Hb}}}{C_{\mathrm{O_2Hb}} + C_{\mathrm{Hb}}}. \tag{3.7}$$

Express your result in terms of

$$R = \frac{\ln\left(\dfrac{I_{\mathrm{DC}}(\lambda_1) + I_{\mathrm{AC}}(\lambda_1)}{I_{\mathrm{DC}}(\lambda_1)}\right)}{\ln\left(\dfrac{I_{\mathrm{DC}}(\lambda_2) + I_{\mathrm{AC}}(\lambda_2)}{I_{\mathrm{DC}}(\lambda_2)}\right)}, \tag{3.8}$$

and discuss the physical meaning of R.

6. Simplify Eq. 3.8 in the case where $I_{\mathrm{AC}}(\lambda) \ll I_{\mathrm{DC}}(\lambda)$. This simplification is approximately correct for pulse oximetry scenario. Hint: use Taylor series.
7. In practice, $\mathrm{SaO_2}$ is often obtained by an empirical calibration curve, e.g., Fig. 4 in the Tremper and Barger paper. Why is the calibration curve different from the equation that we derived above?
8. Find the optical absorption spectra of $\mathrm{O_2Hb}$ and Hb (cite your source). Include the spectra in your answer. Identify the appropriate wavelengths of light that can be used for the detection of each type of Hb.
9. Draw a block diagram of a typical pulse oximeter. Include hardware (e.g. light sources, detectors), signal acquisition and signal processing required to obtain the pulse rate and the oxygen saturation of the user. This should be a higher level diagram; you do not need to go into depth of the precise implementation details of each step.
10. Take a look the commercial pulse oximeter provided. Write a brief description of what each component is responsible for (e.g. light source, detector, display) Include annotated photos/drawings where possible. You should outline how that particular pulse oximeter and its specific parts work. You do not have to tear apart the oximeter.

4 Postlab questions

1. The circuit in Figure 4 consists of a first-order RC high pass filter, a Sallen-Key low pass filter and a non-inverting amplifier. Label which parts of the circuit correspond to each of these functions. Write down the low-pass and high-pass cut-off frequencies. Calculate the gain of the non-inverting amplifier.

2. What affects the accuracy of the pulse monitor that you have built?
3. What advantages does this pulse monitor have compared to other measures of cardiac function? What are its disadvantages?
4. Why do you need to use a sample-and-hold circuit?
5. Discuss the considerations you took into account when choosing the frequency for your driving square waves.
6. Which signal, the pulse or oxygen content, has higher contrast? Why do you think that is?
7. What are the sources of noise in pulse oximetry? How can you prevent/minimize them, e.g. from point of signal processing, user education, device design/construction, etc.?
8. Obtain and analyze plethysomographs and pulse rate information while having the subject do any three of the following.
    - Take a large inhalation and hold it for a few seconds.
    - Laugh out loud. To get the subject to laugh, you can try saying, "There is a fine line between a numerator and a denominator. Only a fraction of people get this joke."
    - Suddenly raise the hand with the probe on.
    - Suddenly raise the other hand.
    - Tap the bench top with the probe finger.
    - Squeeze the probe finger.
    - Cover the finger to block the room light.
    - Anything else you'd like to try.