Oximeter

How to build a pulse oximeter prototype

This document covers the steps required to build and operate a pulse oximeter prototype. Everything from the electrical circuits to the acquisition interface and the Labview software will be covered.

The basics of oximetry

Oximetry generally refers to the oxygen saturation measurement in hemoglobin. It is possible to achieve this through either optical or chemical methods. However, most non-pulse methods often take a lot of time and are invasive. Pulse oximetry is a measurement method that goes back to 1987 and is attributed to the Japanese scientist Takuo Aoyagi. The idea is to use the pulse nature of arterial blood to allow us to circumvent most issues related to techniques employed before 1987. This technology has now become standard and is used extensively in clinics and hospitals.

This document will cover the basics of pulse oximetry, allowing us to measure the relative oxygen saturation of hemoglobin in arterial blood.

Beer's law

Light propagation in a tissue is subject to attenuation. The intensity of the propagating field is attenuated exponentially and follows Beer's law:

$$I(d) = I_0 e^{-\varepsilon(\lambda)\, c\, d},$$

where I_0 is the intensity of the incident field, $I(d)$ is the intensity of the field after a propagation of distance d, ε is the attenuation coefficient and c is the concentration of the absorbing molecule. The total absorbance of a medium containing N different molecules can be expressed as the sum each molecule's absorbance:

$$\varepsilon(\lambda)\, c\, d = \varepsilon_1(\lambda)\, c_1\, d_1 + \varepsilon_2(\lambda)\, c_2\, d_2 + \ \ldots \ + \varepsilon_N(\lambda)\, c_N\, d_N.$$

It is important to notice that optical paths ($d_1, d_2, \ldots$) may differ because of their respective refraction index.

Pulse oximeter

A pulse oximeter is a simple device combining two light emitting diodes (LED) and one photodiode to detect light. The two LEDs are different: the first emits coherent radiation at 660 nm while the second emits at 940 nm. These two LEDs face the photodiode and are separated by a distance d. The patient then puts his finger between the LEDs and the photodiode. At each heartbeat, the blood vessels become engorged with blood, thus increasing the distance d for a short time. Consequently, the intensity detected by the photodiode will vary with time because of the modulation of the optical path.

Human tissues are made of many absorbing substances such as: water, venous blood, arterial blood, pigments, etc. However, out of all the substances that compose the tissue, only the arterial blood pulses with time. This allows us to split the absorbance in two groups. The first corresponds to the absorbance and optical path of constant thickness d_{cte} corresponding to all non-varying substances, while the other relates to the absorption of arterial blood, which will vary between d_{min} and d_{max}. This means that the pulse nature of the heartbeat allows us to separate arterial blood from the other substances that make up human tissues.

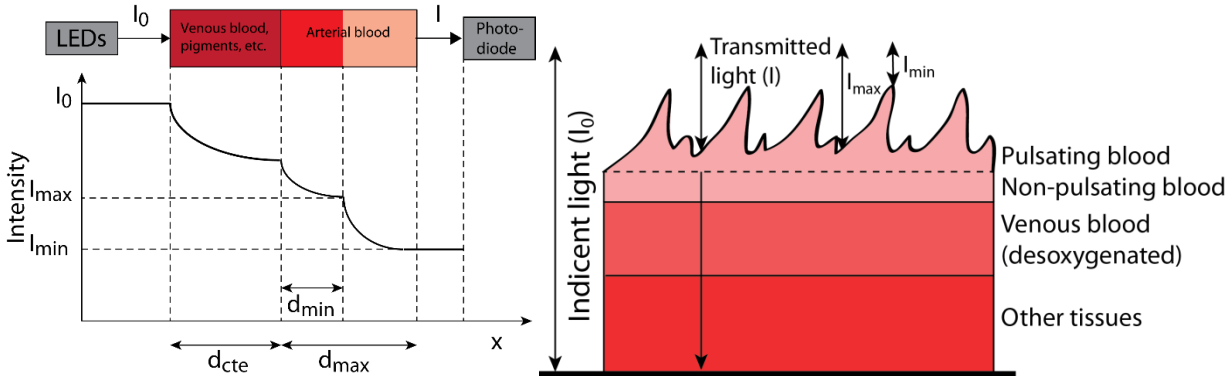

Figure 1 : Attenuation of light during propagation through a tissue. The above graphics link the modulation in optical path d to the modulation of the intensity detected by the photodiode. The constant absorption is the combined effect of different tissues such as venous blood, water, pigments, etc.).

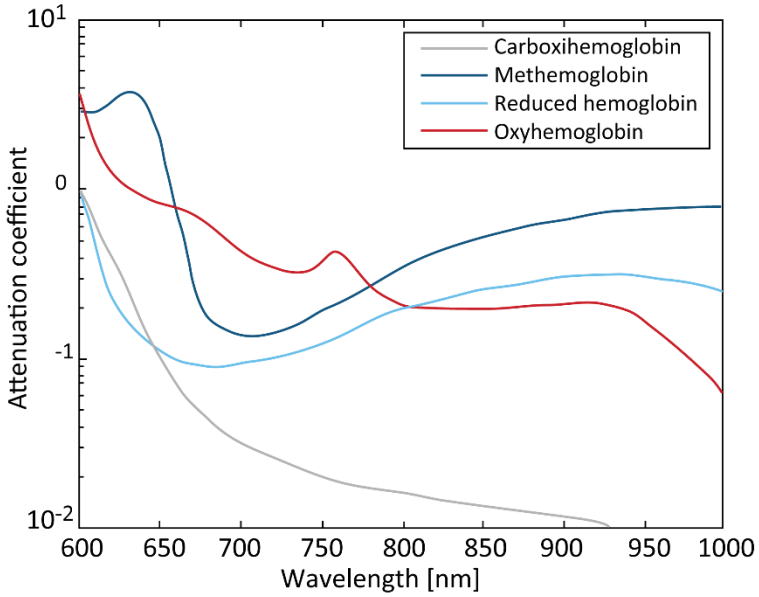

Figure 2 : Attenuation coefficient as a function of the optical wavelength for different substances. It is important to note that hemoglobin has a lower attenuation coefficient than oxyhemoglobin at 660 nm, while has the opposite behavior for infrared (940 nm).

Arterial blood is made of many different molecules. However, the two molecules of interest are reduced hemoglobin (Hb) and oxyhemoglobin (HbO_2), corresponding to the green and black lines respectively (see Fig. 2). Oxyhemoglobin has a greater extinction coefficient at 660 nm than reduced hemoglobin, and vice versa at 940 nm. By measuring the intensity at both wavelengths, it becomes possible to develop a set of two equations (one for each wavelength). The equations allow us to separate reduced hemoglobin from oxyhemoglobin.

With the transmittance measurements of the photodiode, it is then possible to calculate the SpO_2 ratio. This ratio corresponds to the amount of oxyhemoglobin to total hemoglobin, and should be situated between 95% and 100%. A SpO_2 ratio below 90% often indicates a major health problem.

Calculating the SpO_2 ratio

The SpO_2 ratio can be calculated by dividing the concentration of oxyhemoglobin (HbO_2) by the total hemoglobin ($Hb+HbO_2$). This can be expressed mathematically as:

$$SpO_2 = \frac{c_{HbO2}}{c_{Hb}+c_{HbO2}}.$$

The equation above allows us to write the following two relations:

$$c_{HbO2} = SpO_2(c_{Hb} + c_{HbO2}),$$
$$c_{Hb} = (1 - SpO_2)(c_{Hb} + c_{HbO2}).$$

It has been shown that the attenuation of light through a tissue can be expressed as the sum of a constant (DC) attenuation coefficient and an oscillating (AC) coefficient. We know that the intensity will be maximal when blood pressure is at its lowest, while the intensity will be minimal when blood pressure is at its highest. It is now possible to express the maximum and minimum values of intensity mathematically:

$$I_{max} = I_0 e^{-\varepsilon_{cte}(\lambda)\, c_{cte}\, d_{cte}}\, e^{-[\,\varepsilon_{Hb}(\lambda)\, c_{Hb} + \varepsilon_{HbO2}(\lambda)\, c_{HbO2}\,]\, d_{min}},$$
$$I_{min} = I_0 e^{-\varepsilon_{cte}(\lambda)\, c_{cte}\, d_{cte}}\, e^{-[\,\varepsilon_{Hb}(\lambda)\, c_{Hb} + \varepsilon_{HbO2}(\lambda)\, c_{HbO2}\,]\, d_{max}}.$$

In the current set-up, we have to measure the following four items: maximum and minimum intensity at both red ($I_{max,R}$ and $I_{min,R}$ at 660 nm) and infrared ($I_{max,IR}$ and $I_{min,IR}$ at 940 nm). These four quantities allow us to write:

$$R = \frac{\ln(I_{min,R} / I_{max,R})}{\ln(I_{min,IR} / I_{max,IR})} = \frac{\varepsilon_{Hb}(\lambda_R)\, c_{Hb} + \varepsilon_{HbO2}(\lambda_R)\, c_{HbO2}}{\varepsilon_{Hb}(\lambda_{IR})\, c_{Hb} + \varepsilon_{HbO2}(\lambda_{IR})\, c_{HbO2}}.$$

We replace the concentrations c_{HbO2} and c_{Hb} by their respective expressions:

$$R = \frac{\varepsilon_{Hb}(\lambda_R) + [\varepsilon_{HbO2}(\lambda_R) - \varepsilon_{Hb}(\lambda_R)]\, SpO_2}{\varepsilon_{Hb}(\lambda_{IR}) + [\varepsilon_{HbO2}(\lambda_{IR}) - \varepsilon_{Hb}(\lambda_{IR})]\, SpO_2}.$$

This allows us to write the SpO_2 ratio as a function of R:

$$SpO_2 = \frac{\varepsilon_{Hb}(\lambda_R) - \varepsilon_{HbO2}(\lambda_{IR})\, R}{[\varepsilon_{Hb}(\lambda_R) - \varepsilon_{HbO2}(\lambda_{IR})] + [\varepsilon_{HbO2}(\lambda_{IR}) - \varepsilon_{Hb}(\lambda_{IR})]\, SpO_2}.$$

The attenuation coefficients are well known and are presented in the following table:

	λ (nm)	ε_{Hb} ($mM^{-1}\,cm^{-1}$)	ε_{HbO2} ($mM^{-1}\,cm^{-1}$)
λ_R	660	0,81	0,08
λ_{IR}	940	0,18	0,29

Hardware requirements

Here is the list of the required components to build a pulse oximeter prototype:

Qty.	Description and part number	Supplier	Price
1	SpO_2 probe (CST060-3120)	Nellcorr	55$
1	Multifunction DAQ (USB-6008)	National Instruments	190$
1	Solderless readboard		-
1	Operational amplifier (OP27)		-
1	9 volts battery		-
2	Transistors (2N3904)		-
	Resistances		-

LabView programs required for the operation and acquisition are provided on the CD-ROM that comes with this document (note that they are also available online at www.femto.ca). The files are: *oxymetre.vi*, *calcul.vi*, *peak.vi*, *pouls.vi*, and *SpO2.vi*.

Experimental set-up and electrical circuitry

Figure 3 shows the pulse oximeter prototype. It is made of a SpO_2 probe DS-100A connected by a DB9 plug to a breadboard. The breadboard is then connected to the acquisition module NI USB-6008. The acquisition module is controlled by a software built with Labview, provided on the CD-ROM. We will be using the analog outputs *AO0* and *AO1* (orange wires) and the analog input *AI0* (green and yellow wires) along with a +5V, 200mA voltage source (black and white wires).

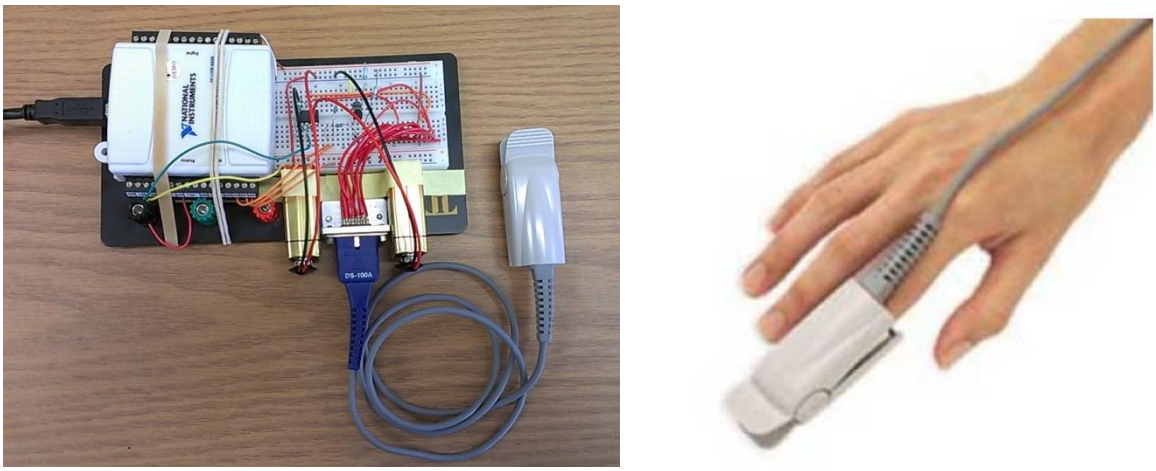

Figure 3 : Pulse oximeter prototype. We can see the Nellcor SpO_2 probe connected to the DB9 plug. The DB9 plug itself is connected to the breadboard and to the acquisition module.

The control circuits are shown below (fig. 4). The dashed rectangle represents the oximeter itself. It is made of two LEDs (one red, one infrared) and one photodiode (detector). The idea here is that only one LED at a time must be active. In order to achieve this, the diodes are connected facing each other such that when current goes from *Ox2* to *Ox3*, the infrared diode is activated and vice versa if the current goes in the other direction. It is possible to assemble this circuit using the components provided.

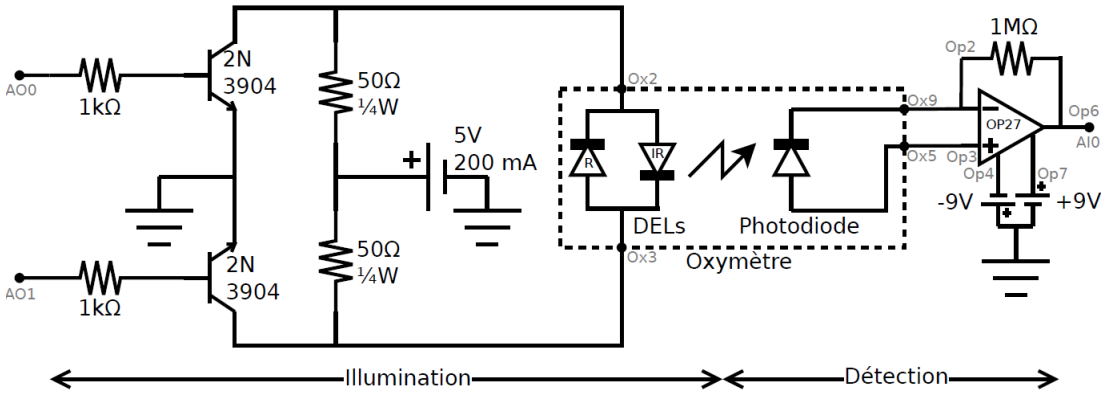

Figure 4 : Schematics of the electrical circuit. It consists of two sections, one for illumination and one for detection. The dashed box is the probe.

To prevent damage of our LEDs, it is desirable to power them the least amount of time possible. In order to do this, we alternate power between the red and infrared diodes and add a downtime where both LEDs are powered off. This means that each diode only has to work 33% of the time. The simplest way to achieve this would have been to plug in a voltage source directly to the USB module and send in a square signal. However, its output power is not strong enough for our diodes. This is why we will be using the analog outputs *AO0* and *AO1*. These analog outputs will

then be used to control two transistors (type 2N3904, see below) that will act as a valve for a high power voltage source. The +5V, 200 mA voltage source on fig. 4 is provided by the USB-6008 module. Let's consider the following situation: the AO0 is at +5V while the *AO1* is at 0V. In this situation the bottom transistor is in an open position, while the top transistor is closed (allows conduction). The current from the +5V,200 mA source will then take the lower branch, through the red LED to finally reach the ground through the top branch. However, if *AO0* is at 0V and *AO1* is at +5V, the current will travel in the opposite direction. In this case, it will take the top branch, power the IR LED, and finally reach the ground through the bottom branch. We can control the intensity of the LEDs by adjusting the voltage applied at the transistors.

Now let's move to the detection side of the electrical circuit. This side is simpler and only consists of a photodiode amplified through an operational amplifier, with a retroaction loop of either 1 MΩ or 2 MΩ[1]. The chip is powered by two electric batteries of ±9V. The output is Op6 and is connected to the acquisition module *AI0*.

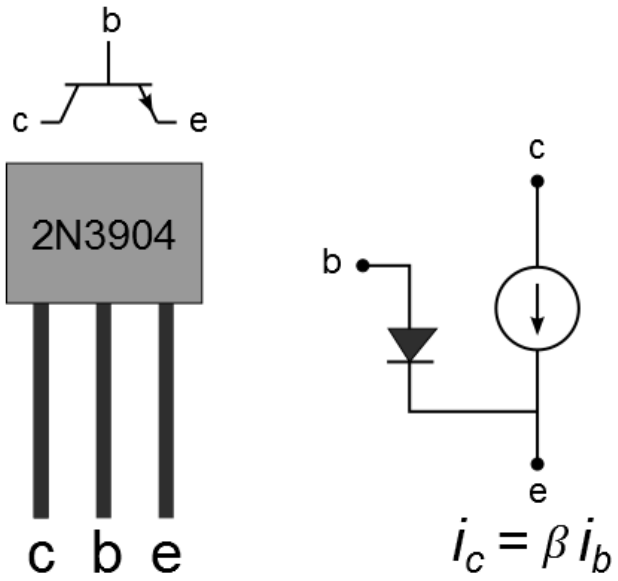

Figure 5 : Transistor 2N3904. This transistor consists of a base *b*, a source *e* and a collector *c*. The transistor acts as a valve and limits the current i_c for the collector and it is controlled by the base current i_b. If the intensity i_b at the base is too high, the transistor is considered completely open. The gain parameter for this transistor is between 40 and 100.

[1] It is possible to use 1M Ohms; this is what was initially used. However, it is recommended that you use 2M Ohms resistance because it facilitates the detection of the signal. Use whichever works best for you.

Labview program: an overview

Labview programs are used to acquire data. They are provided and located on the CD-ROM that comes with this document. The files are: *oxymetre.vi*, *calcul.vi*, *peak.vi*, *pouls.vi*, and *SpO2.vi*.

Here is an overview of the different programs. The following pages will provide you with illustrations explaining each program. If you would like to know more about these programs, the source code can be found on the CD-ROM (or online at www.femto.ca).

The main program is called *oxymetre.vi*. This file contains three main loops. From the outside going in we have: a *while* loop, that keeps the program running until the user presses *stop*; a *sequential* loop that reads the photodiode and writes voltage values; and finally a *conditional* loop that indicates the color of the photodiode (red, infrared or neither), and runs the sub-routine *calcul.vi.* To the left of the loop is a section dedicated to initialize the channels while on the right is a section dedicated to terminate the channels and write the *log.txt* file. The data is written in this log file after each use.

Calculus subroutines are controlled by the program *calcul.vi*. First, the calculus program will call peak.vi to extract the information related to the wavelength and the amplitude of the maximums and minimums for the intensity. This information is then sent to the subroutines *pouls.vi* and *SpO2.vi*, used to calculate the pulse and the SpO_2 ratio respectively. The SpO_2 ratio is calculated using the method described above in this document while the pulse is simply calculated by averaging the time between the two intensity peaks.

In the next pages, we provide you with illustrations for each Labview program:

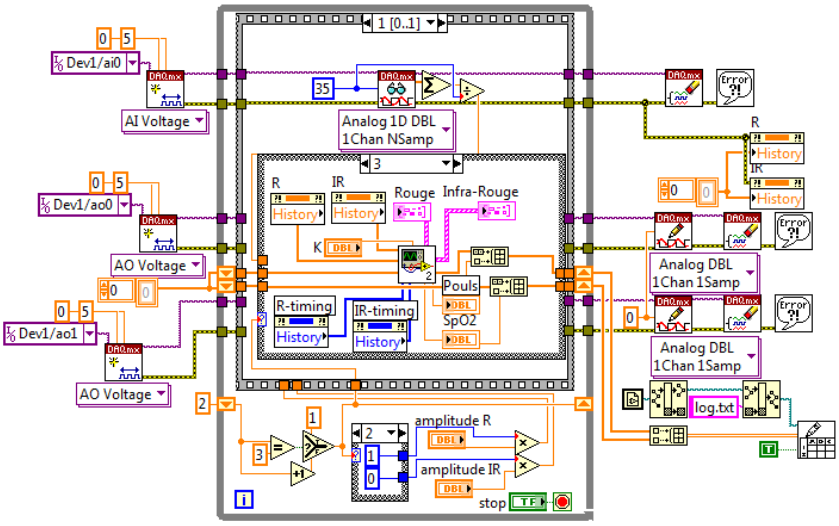

Figure 6 : *Oxymetre.vi* is the main program file that controls the probe.

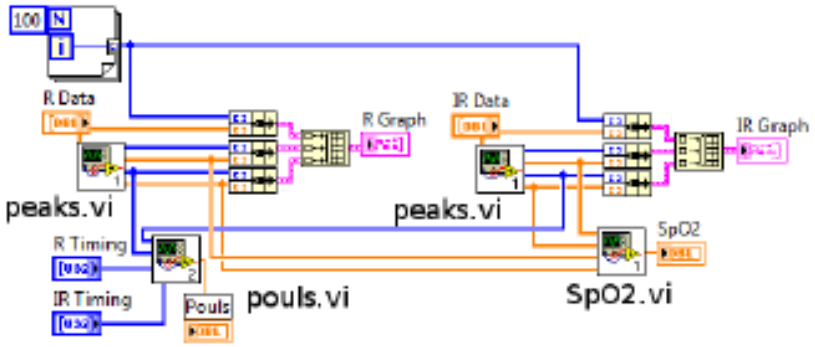

Figure 7 : *Calcul.vi* controls the other calculus subroutines.

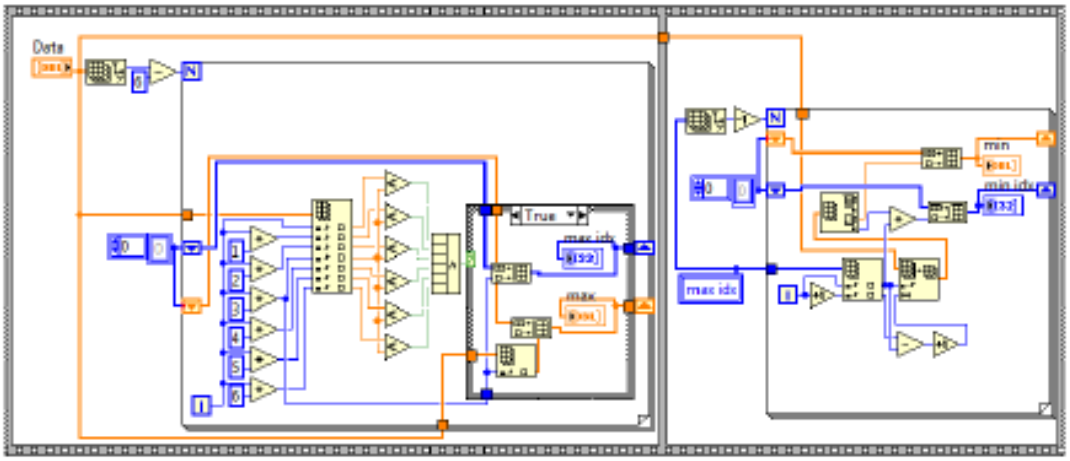

Figure 8 : *Peak.vi* reads the min and max values of the intensity detected by the photodiode.

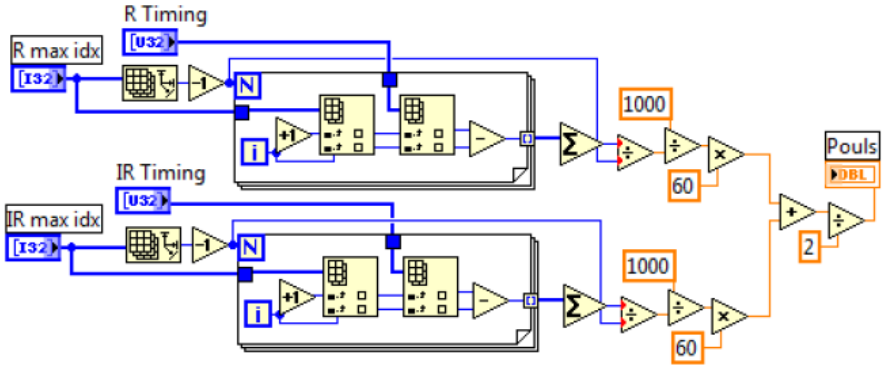

Figure 9 : *Pouls.vi* calculates the pulse.

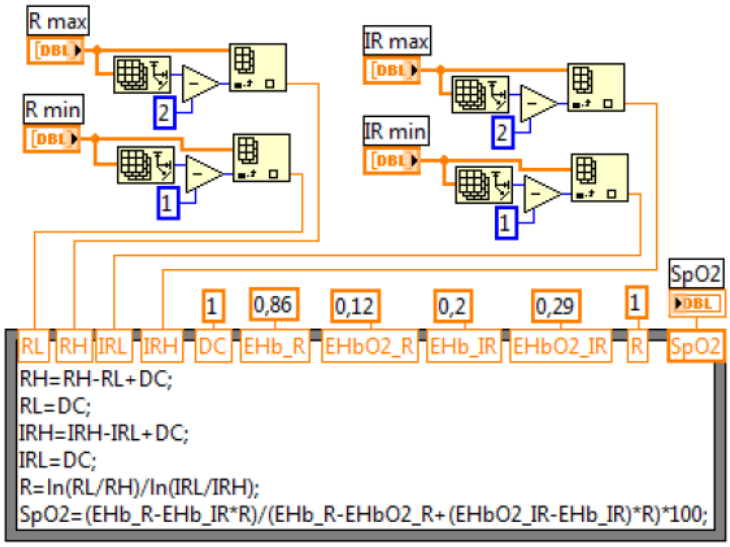

Figure 10 : *SpO2.vi* calculates the SpO_2 ratio.

Using the pulse oximeter prototype

Once everything is connected together (acquisition module, batteries and probe), the pulse oximeter is good to go! Just put in your index, keep your arms slightly elevated and press on the white arrow ("run") in the Labview program. The default configuration for the software is set at 1.2V for the infrared and 3.5V for the red LEDs, while the value for the calibration constant K is set at 0.7 A.

Now just relax and keep calm. You should see a DC baseline of 3-4V and an AC pulse signal of about 0.1 V. Do not go over 5V since the acquisition card will not record values over 5V. The green values correspond to the maximums, while the red values correspond to the minimums.

You should be able to see the pulse and the SpO_2 ratio on the screen. The *log.txt* file will also be created in the same folder as the software.

You may also go and climb some stairs to raise your pulse. Modifying your SpO_2 ratio will prove harder. To see a difference, you would need to go and have a heavy workout immediately before coming to the laboratory. If you are quick enough, you will be able to measure your SpO_2 ratio before it goes back to normal.

Known problems

1. **Noisy signal**
   The connections on the breadboard can loosen up with time, which causes the setup to be susceptible to vibrations. This increases the base level of noise of our system. Using the same setup on a welded circuit would help a lot to reduce vibrations.

2. **The batteries have a short lifespan**
   A weak or noisy signal often means a dead battery. To circumvent this issue, the batteries have to be replaced frequently. This issue is partly exacerbated by the fact that the current setup does not include a switch. Unplug the batteries after each use to increase the lifespan of the batteries.