Pulse oximeter: study and design

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Abstract: Monitoring heart rate is crucial in various medical settings and blood oxygen saturation ($Sp0_2$) is a key indicator of the body's oxygen-carrying capacity. In this project we will present a study of the theoretical part behind a pulse oximeter. We also explain the design of the electronic system with elements and components studied in the physics degree. Experimentally, we choose the right components to be able to create the electric circuit on a protoboard. This allows us to verify theoretical aspect and check the signal status.

I. INTRODUCTION

The pulse oximeter is a medical device that tracks changes in light absorbance as blood pulses. It is a non-invasive method that allows the determination of heart rate and blood oxygen saturation using photoelectric methods. This device converts variations in the received light at the optical detector into an electrical voltage of the order of volts. Additionally, it attenuates possible interference and unwanted components at the input to the microprocessor to be able to process the different received signals.

Heart rate, also known as pulse, is the number of times that heart betas or contracts during a certain time. In a healthy adult at rest, it oscillatse between sixty and one hundred beats per minute. Blood oxygen saturation, commonly referred to as SpO2 (peripheral capillary oxygen saturation), is the amount of oxygen in body fluids, in this case, in blood.

Over the years, advancements in technology have led to the development of compact, portable, and user-friendly pulse oximeters, making them more accessible for personal use. These devices are now commonly used by athletes, fitness enthusiasts, and individuals with respiratory conditions, enabling them to monitor their oxygen levels and make informed decisions about their physical activities.

The aim of this work is to have a comprehensive understanding of the underlying principles and components of a pulse oximeter, and to design its electric circuit in a low-cost manner.

This report is structured as follows. In section II, we define fundamental concepts and principal equations, highlighting their relevance to our device. In section III, we provide a detailed description of the electronic circuit responsible for signal transformation. Moving forward, in section IV, we discuss the selection of components and present the finalized circuit design, providing a visual representation of the completed circuit.

II. THEORETICAL DEVELOPMENT

On the one hand, it is necessary the biological principals. The detection of the pulse through light is called photoplethymography (PPG), which is the optical acquisition of a plethysmography. Its definition according to NLM ("National Library of Medicine") is "a simple and low-cost optical bio-monitoring technique used to non-invasively measure the blood volume changes that occur in the microvascular tissue bed beneath the skin, which are due to the pulsatile nature of the circulatory system" [1]. In addition, it is essential to have a light source and a photo detector because it an optical method. It usually use LED's with wavelength of red and IR owing to have the maximum difference of extinction coefficient between oxygenated hemoglobin ($Hb0_2$) and deoxygenated hemoglobin (RHb) as it seen in figure 1.

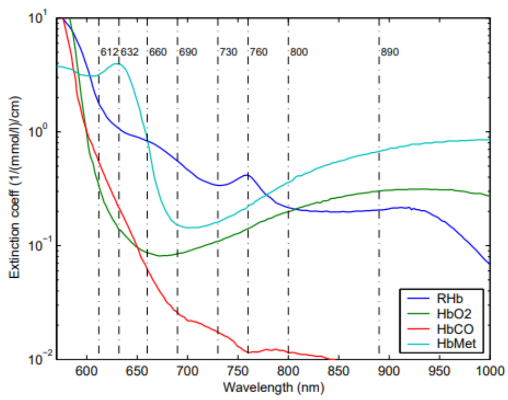


FIG. 1: Extinction coefficients of the different hemoglobin species.

On the other hand, the measurement principle of oximetry is based on the Beer-Lamber law (Eq. 1). Beer law says transmitted light intensity decreases exponentially as concentration of substance increases. Lamber law says transmitted light intensity decreases exponentially as travelled length increases [2].

$$A = -\epsilon(\lambda)c(x-d) \quad (1)$$

where $\epsilon(\lambda)$ is the extinction coefficient of the substance at a given wavelength λ of light, d is the length of the light path, and c is the concentration of the substance (3.3.1, [3]). Moreover, as it knows transmittance (T) and absorbance (A) are logarithmically related.

$$A = -ln(T) = -ln(I/I_0) \quad (2)$$

As the heartbeat varies in time, the time derivative of absorbance must be evaluated. As can be seen in the figure 2, in the practice the signal of photo detector is divided in the DC-component (DC_λ), which is the transmitted light during diastole and it gives the total absorbance, and the AC-component (AC_λ), which is the maximum value in the systole (4.4.2, [3]). Where λ references to wavelength of IR ($880nm$) and red ($650nm$) light. For calculation is utilized a concept called *ratio-of-ratios* R:

$$R = \frac{A_{t,R}}{A_{t,IR}} = \frac{dAC_{\lambda_1}}{dAC_{\lambda_2}} = \frac{AC_{\lambda_1}/DC_{\lambda_1}}{AC_{\lambda_2}/DC_{\lambda_2}} \quad (3)$$

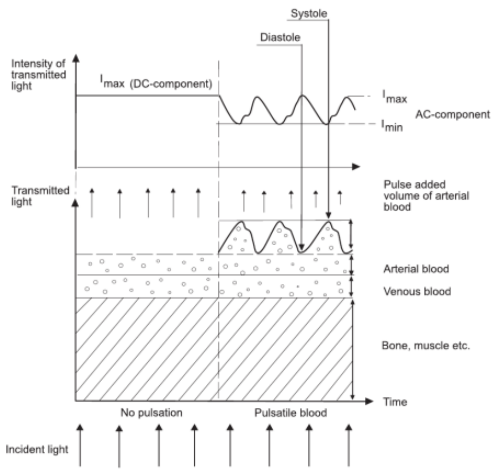


FIG. 2: Transmitted light during PPG measurement [4].

Furthermore, the ratio R is related to oxygen saturation, which is the measurement of oxygen carried by the blood compared to its total capacity. We employ the delta absorption method, which use polynomial approximation of theoretical Beer-Lamber calibration curve (page 15, [4]). If we make straight line approximation, and take into account that for $R = 1$ it gives $Sp0_2 = 85\%$ and for $R = 0.5$ is gives $Sp0_2 = 100\%$, the calibration equation is:

$$Sp0_2 = 115 - 30 * R \quad (4)$$

III. DESING OF THE ELECTRONIC SYSTEM

When it comes to carry out the implementation, it uses stage-by-stage strategy. The program employed for the circuit and simulations is *LTSpice*. It is necessary to make a good processing of the signal because AC-component is only *2%* of the total signal.

The first stage is optical sensor, it employ a red LED, an IR LED and a photo-transistor as light receiver (fig. 3). Moreover, connections go to Arduino to be able to switch the states that will cause the alternating activation of the two different LED's.

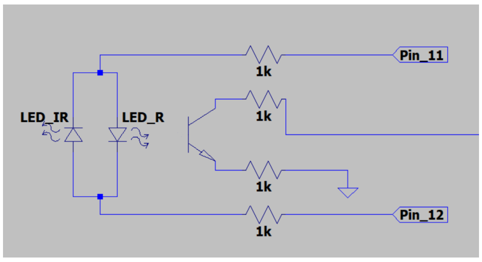


FIG. 3: Optical sensor.

The next stage is a transmittance amplifier, which amplifies the signal to mV, and a demultiplexer 1:2 with logic gates to be able to differentiate the two signals (one from IR light and one from red light) (fig. 4).

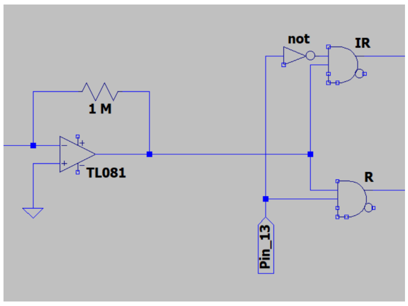


FIG. 4: Transmittance amplifier and demultiplexer.

Afterwards, each signal will have the same treatment. The signal coming out of one of the logic gates is connected to condenser in order to not lose voltage. After it goes a voltage follower so the phases and cutoff frequencies of the next filtering stage are not affected by the condenser.

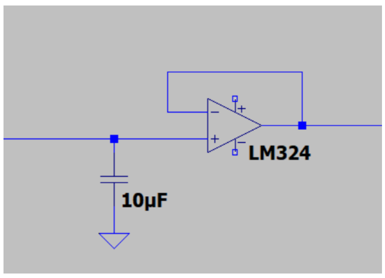


FIG. 5: Condenser and voltage follower

At this point the signal can be shown in an oscilloscope. However, this signal is very noisy and with a very low amplitude. In order to improve the quality, it uses second order Sallen-Key filter that is represented in figure 6. With this filter the lower frequencies will be remove and, at the same time, the signal will be amplified.

$$H_2(s) = \frac{V_0}{V} = \frac{H_0}{As^2 + Bs + 1} \tag{5}$$

$$\frac{1}{\omega_0^2} = R_6 R_7 C_1 C_2 \tag{6}$$

$$Q = \frac{\sqrt{R_6 R_7 C_1 C_2}}{R_6 C_2 + R_7 C_1 + R_6 C_1 - H_0 R_6 C_2} \tag{7}$$

Equation 5 is the transfer function of the filter where $A = R_6 R_7 C_1 C_2$, $B = R_6 C_2 + R_7 C_1 + R_6 C_1 - H_0 R_6 C_2$ and $H_0 = 1 + R_{11}/R_9$. From the equation 6 the resonant frequency of the filter (w_0) is found. Finally, the equation 7 is use for known the gain of the low-pass filter [6].

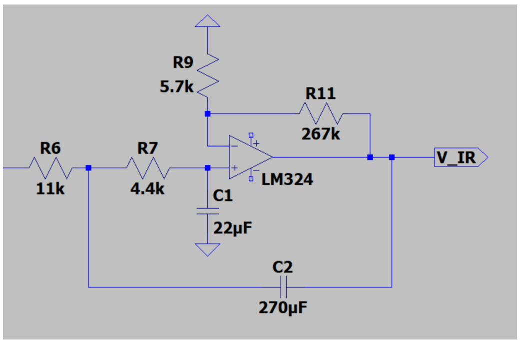


FIG. 6: Second order Sallen-Key filter

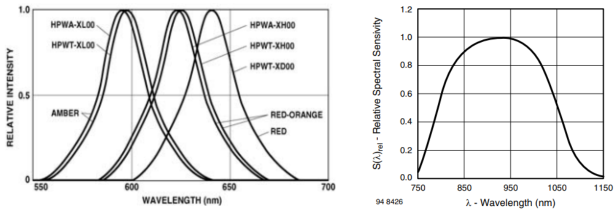
IV. EXPERIMENTAL DEVELOPMENT

In this section, it deals with each of the components and instruments used to carry out the circuit.

The first stage, optical sensor, is the most complex part because it is really necessary that all of the components have the correct qualities. As red LED is use **LPR** component, whose wavelength is compress between $600 - 650nm$ and it has a 'piranha' shape (fig. 7a). As IR LED is utilise a **BPV22NF** component, whose wavelength range is $870 - 950m$ (fig. 7b). As the last component, photo transistor, is a **BPW34** component, which has an adequate detention range for what it need (fig. 8) [7].

For the transmittance amplifier it use the operational amplifier (AMPOP) **TL081CP**, which must be biased to -15V and 15V [7].

At this point, the signal can be visualized in oscilloscope. In the figure 9 is possible to see small marked variation of $12mV$. In addition, the peak-to-peak value of the signal is of $528mV$.



(a) Red LED (b) IR LED

FIG. 7: Relative spectral sensitivity vs. wavelength

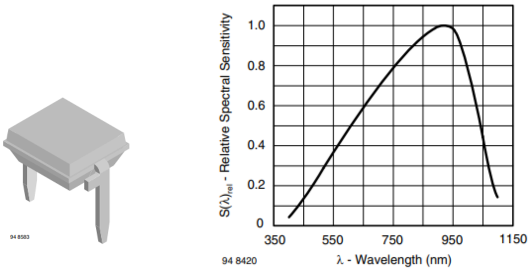


FIG. 8: Photo-transistor: (a) shape and (b) Relative spectral sensitivity vs. wavelength

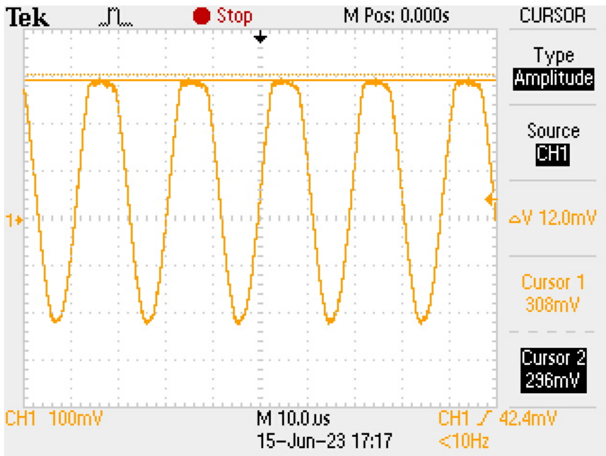


FIG. 9: Signal in oscilloscope

For the next stage, separation of the signal (demultiplexor), it utilise two components of logic gates, in of AND gates **SN74LS32N** and one of NOT gates **SN74LS04** [7]. These components have 4 logic gates and they are polarized between 0V and 5V.

For the last stage, treatment of the red and infrared signal separately, the component **LM324N** has been utilised [7]. Using this component, which contains 4 AMP-OP, is possible to make the remaining circuit with just one unit. It should also be biased to -15V to 15V.

Additionally, the figure 10 is the simulation with LT-space of second order Sallen-Key filter. But the slope of the amplitude, in decibels (dB), should diminish 40dB/decade and as can be seen it decrease just 20dB/decade.

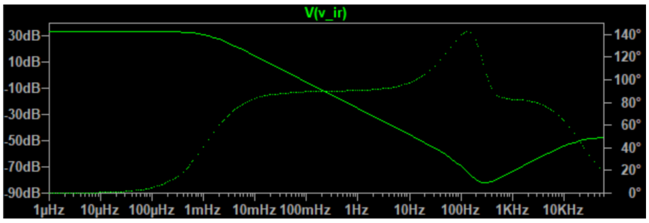


FIG. 10: Second order Sallen-Key filter simulation

The experimental electronic circuit is represented in figure 11, it is done in a protoboard.

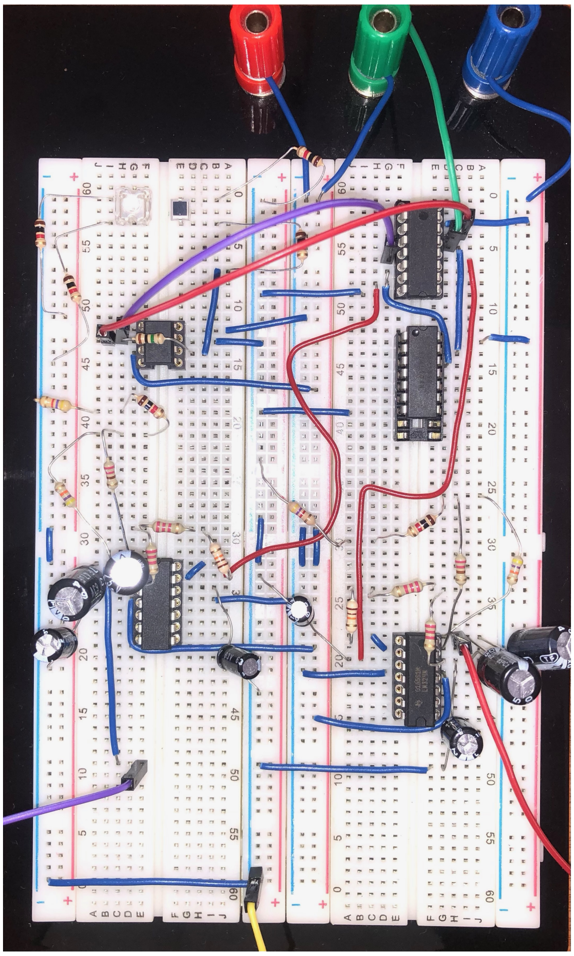


FIG. 11: Experimental electronic circuit

V. CONCLUSIONS

On the one hand, from figure 9 we found a little variation of $12mV$. It makes reference to signal variation caused by heartbeat for red light. If we do the calculation $\Delta V/V_{p-p} = 12/528 = 2.3\%$ and it is exactly the theoretical 2% of the AC-component that has been commented on section III.

On the other hand, the signal at circuit's end it is very difficult to use. This probably happens because second order Salle-Key filter work has one of first order. At this point, one possibility for the future it can be change the final stage of the initial electronic circuit. As can be seen in figure 12, with first order Sallen-Key filter the results are better. The resonant frequency of filter now is given by $w_0 = \frac{1}{R_1 C_1}$, which gives $f_1 = 10Hz$, and its gain by $H_0(s) = (1 + \frac{R_b}{R_a})$, which is 2.46.

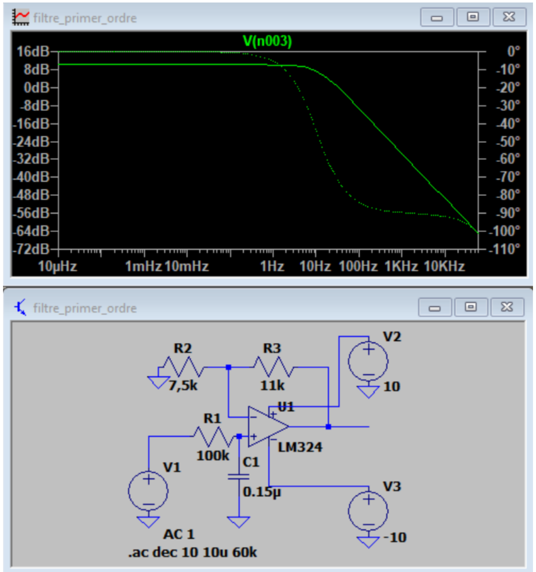


FIG. 12: First order Sallen-Key filter and it simulation

Acknowledgments

I would like to thank Anna Vila for her help and guidance throughout this work, and all the time she dedicates with looking for the components and equipment required. As well as my family, friends, and my partner to give me support to finish my degree and my final degree project.

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