



Blood Pressure Monitoring with Photoplethysmography

Group 7
Inês Carvalho 92812
Inês Cunha 92813
Mariana Mourão 98473

MSc in Biomedical Engineering

Instrumentation and Acquisition of Biosignals

Prof. João Sanches
Prof. Hugo Plácido da Silva
Dr. Luís Brás Rosário
Eng. Afonso Raposo

April 2022

Abstract

In this project, it was build a prototype which integrates a single-site Photoplethysmogram (PPG) sensor for the real-time Blood Pressure (BP) monitoring, as the changes in the pulsatile blood flow volume optically detected are correlated to the BP variations during the cardiac cycle. The proposed prototype comprises a reflectance mode PPG, in which an infrared Light-emitting diode (LED) and photodetector were placed at the same side of the fingertip (selected measurement site). The PPG signal was subsequently pre-processed in the analog domain, in which a high-pass filter, an active low-pass filter and an inverting buffer were used.

The acquired PPG signal was sampled in Arduino, with a sampling frequency of 30 Hz, allowing for a non-aliasing representation of the signal. The post-processing was done in Python, in order to calibrate and normalize the PPG signal to the values of the arterial blood pressure previously measured by a cuff-based device. This provides a derivation of the BP waveform from the acquired PPG signal, which could be used for further classification (clinical applications). An interactive Graphical User Interface (GUI) was developed for performing the calibration and real-time monitoring of the BP.

For evaluating the performance of the device, 12 subjects underwent examination with their arm rested. The experimental results show that the proposed device is potentially reliable and facilitates efficient BP monitoring.

Keywords

Blood Pressure (BP), Photoplethysmogram (PPG), signal processing, analog domain, filter, Graphical User Interface (GUI)

Contents

1 Problem Statement	1
1.1 Background	1
1.1.1 Photoplethysmography	1
1.1.2 Blood Pressure estimation with Photoplethysmography	2
1.2 Motivation	4
1.3 Objectives	4
2 Project Management	5
2.1 Development Roadmap	5
3 Methodology	6
3.1 Photoplethysmography Sensor	6
3.1.1 Final hardware	10
3.2 Software	11
3.2.1 Block diagram	18
3.3 Testing	19
3.4 Materials	19
3.5 Expected Impact	19
4 Results and Discussion	20
A Results	22
Bibliography	22

List of Figures

1.1 PPG sensor in reflection mode [1]	2
1.2 PPG signal [2]	2
1.3 Time comparison between BP, Electrocardiography (ECG) and PPG waveforms, being graphically represented the Pulse Transit Time (PTT). Adapted from [3]	3
3.1 Circuit Diagram for the IR emitter and optical sensor TCRT1000 . [4]	7
3.2 RC Hight-Pass Filter. For our circuit, V_{in} is the V_{sensor} previously explained.	7
3.3 First stage of signal conditioing: High pass filter (HPF), previously seen, and Active Low-Pass Filter (LPF) (with an Operational Amplifier (Amp op))	8
3.4 Final scheme of the derived circuit. The sensor circuit can be seen in Figure 3.1.	9
3.5 First version of the hardware of the PPG sensor circuit.	10
3.6 Second version of the hardware of the PPG sensor circuit.	10
3.7 Final (prototype) version of the hardware of the PPG sensor circuit.	11
3.8 User Interface example, with the values of 117 and 76 mmHg taken from a subject.	12
3.9 Example of the raw PPG signal. The minimum value is approximately 0, and the maximums are approximately 150.	12
3.10 Graph that pops up after the user adds the measured data of the systolic and diastolic pressure of a subject. The blue dashed lines represent the threshold in which the relative maximums and minimums were ignored. The red lines represent the mean of the absolute maximums and minimums.	14
3.11 Message pop-up with the calibration factor of one subject.	14
3.12 Acquired calibrated data from a subject. The minimum value is approximately 70 and the maximum 120. For this subject, a systolic pressure of 117 and diastolic pressure of 76 mmHg were previously measured.	17
3.13 Block diagram with step-by-step data acquisition.	18
A.1 Results of subject 1.	22

A.2 Results of subject 2.	23
A.3 Results of subject 3.	23
A.4 Results of subject 4.	24
A.5 Results of subject 5.	24
A.6 Results of subject 6.	25
A.7 Results of subject 7.	25
A.8 Results of subject 8.	26
A.9 Results of subject 9.	26
A.10 Results of subject 10.	27
A.11 Results of subject 11.	27
A.12 Results of subject 12.	28

List of Tables

4.1 Obtained results of a total of 12 subjects.	20
---------------------------------------------------------	----

Acronyms

PCB	Printed circuit board
PPG	Photoplethysmogram
LED	Light-emitting diode
LPF	Active Low-Pass Filter
Amp op	Operational Amplifier
ECG	Electrocardiography
BP	Blood Pressure
PTT	Pulse Transit Time
PWV	Pulse Wave Velocity
PD	Photodetector
SBP	systolic blood pressure
DBP	diastolic blood pressure
AC	Alternative Current
DC	Direct Current
GUI	Graphical User Interface

1. Problem Statement

1.1 Background

Blood Pressure (BP) constitutes one of the most important physiological signals for the detection, diagnosis, and monitoring of cardiovascular and hemodynamic diseases [5]. The BP corresponds to the amount of blood power within the arteries. At each heartbeat, an electro-mechanical signal is generated in the heart by the contraction of the left ventricle during systole, producing a pressure wave into the aorta, which will propagate to the peripheral arteries. When this ventricular contraction occurs, the maximum BP is registered, being denoted as the systolic blood pressure (SBP), typically around 120 mm Hg. During diastole, the heart muscle relaxes and the blood returns from the periphery towards the heart, with the BP decreasing between heartbeats. The minimum BP is registered exactly after the beginning of next the ventricular ejection, being denominated diastolic blood pressure (DBP), usually about 80 mm Hg [6] [7] [8] [9].

Cuff-based devices remain the standard method for measuring the BP, delivering the highest measurement accuracy but without being possible to continuously measure the BP [9] [10]. Over the past decades, the technology development has revolutionized the healthcare industry in prevention, diagnosis and treatment. In particular, the monitoring of the cardiovascular system has increased tremendously in the last decade, due to the increased accessibility and ease of use of cardiovascular monitoring devices, such as Electrocardiography (ECG) and Photoplethysmogram (PPG).

1.1.1 Photoplethysmography

Photoplethysmography, or PPG, is an optical technique which utilizes a light source (a LED) and a Photodetector (PD) to continuously monitor the change in blood volume in the microvascular bed of subcutaneous tissue, as a function of light either transmitted through or reflected from the skin [6] [9] [10].

Depending on the relative positions of the LED and the PD, two distinctive modes of operation are possible for PPG: transmissive mode, in which the transmitted light is detected by a PD positioned opposite to the LED; reflectance mode, where the optical elements are located on the same surface, with the PD detecting the light backscattered or reflected from tissue, bone, and/or blood vessels (see Figure 1.1) [1] [11].

The PPG signal is formed by two components (see Figure 1.2): the Direct Current (DC) component, which is a function of the light source and the constant light absorption by the tissues in the optical path, as well as average blood volume, respiration, sympathetic nervous system activity and thermoregulation; the Alternative Current (AC) component, which reflects the changes in blood volume that occur between

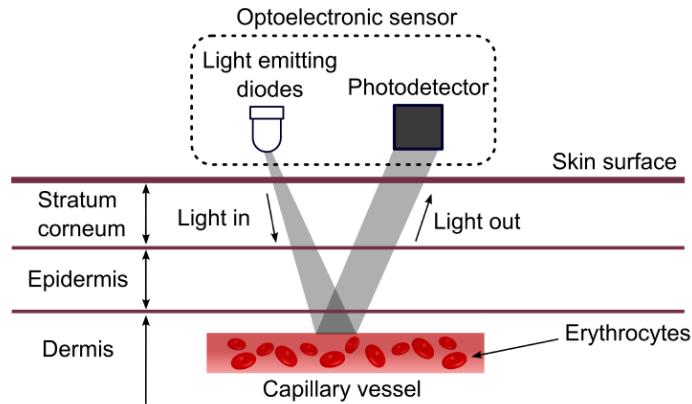


Figure 1.1: PPG sensor in reflection mode [1]

the systolic and diastolic phases of the cardiac cycle, having a fundamental frequency related to the heart rate. The PPG signal is in the range of 0.5 - 4 Hz. [1] [6] [11].

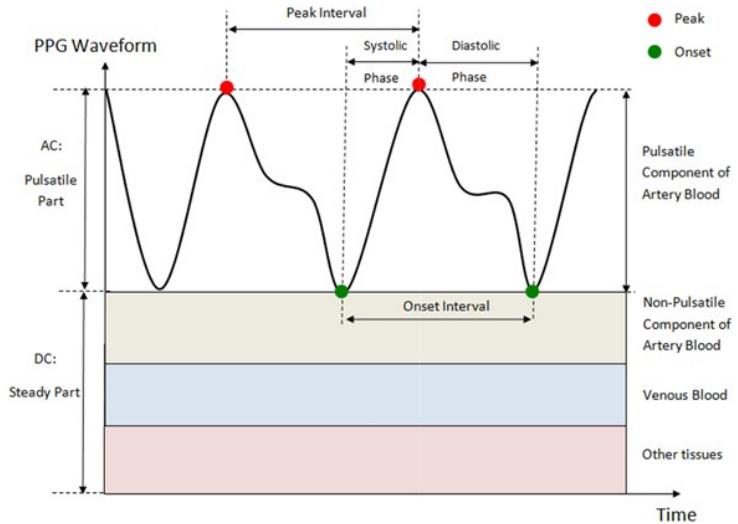


Figure 1.2: PPG signal [2]

This technique is gaining popularity over the years as an alternative to the conventional ECG, mainly due to the simplicity of its operation, the wearing comfort ability for its users, and its cost effectiveness.

1.1.2 Blood Pressure estimation with Photoplethysmography

For BP monitoring, PPG-based Pulse Wave Velocity (PWV) techniques are well established, allowing to measure the speed of the blood flow, namely, the time interval for the blood pressure wave originating from the heart to reach a peripheral site. This time interval is called Pulse Transit Time (PTT), being usually set to the time interval between R-wave in the ECG signal and the systolic peak of the PPG signal (see Figure 1.3). PTT varies inversely with the BP, since when vessels are stiffer or more contracted,

the blood travels faster and exerts more pressure. Contrarily, when vessels are more relaxed or elastic, the blood travels more slowly and exerts less pressure [9]

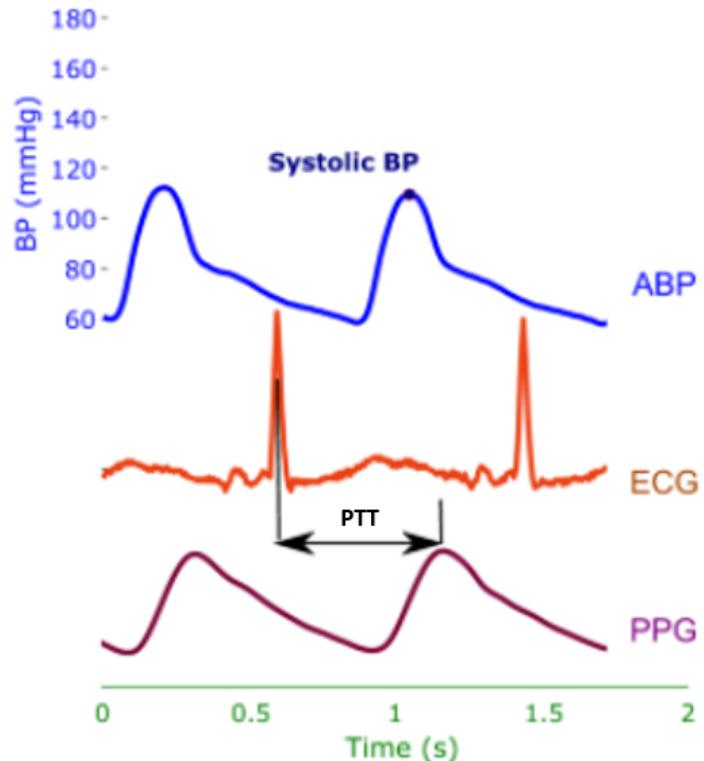


Figure 1.3: Time comparison between BP, ECG and PPG waveforms, being graphically represented the PTT.
Adapted from [3]

As previously mentioned, PPG signal translates blood volume variations, rather than the pressure in the blood vessels, since the amount of optical absorption or reflection depends on the blood volume that is present in the optical path [3]. Although, because the blood volume in the peripheral arteries is directly related to the pressure exert on them, it has been proven that the PPG signal produces pulse waveforms with a good correlation with BP waveforms (see Figure 1.3) [3] [12]. In fact, the systolic component of the PPG signal (see Figure 1.2) is the result of the blood pressure propagation from the left ventricle to the distal place where the signal is acquired. As for the diastolic component of the PPG signal, it is formed by the blood pressure being transmitted from the ventricle along the aorta to the lower part of the body, where it is reflected from small blood vessels towards the aorta and the distal place, originating the diastolic peak (see Figure 1.2) [6] [13].

1.2 Motivation

Hypertension is considered the main risk factor for cardiovascular diseases, being a long-term condition in which the BP in the arteries is persistently elevated, contributing largely to the mortality and morbidity around the world [3] [5]. Consequently, there is still a great demand for the development of technologies for detecting, diagnosing and monitoring continuous and non-invasively the BP [5]

To effectively measure the BP, cuff-based methods and the calculation of the PTT remain the most well-established approaches. This compromises the portability and feasibility for continuous monitoring. This reality constitutes one of the driving forces of this work, which is to further contribute to producing evidence on the clinical feasibility of a stand-alone PPG device to continuously monitoring the BP.

1.3 Objectives

This project has the goal of building a system for real-time monitoring the BP, by conceiving a PPG sensor prototype properly calibrated to translate the variations of the BP during the cardiac cycle. It is intended to evaluate the feasibility of the conceived device, by designing an appropriate experimental protocol.

2. Project Management

2.1 Development Roadmap

The following list illustrates the project's milestones.

1. Defining and clarifying the project goal.
 - (a) Understand the aim of the project in the context of the course (Requirements Elicitation and Analysis);
 - (b) Brainstorming, defining the aim of the project;
 - (c) Researching and reading;
 - (d) System designing, circuit design, defining functionalities, block diagram.
2. Implementation and Development.
 - (a) Development of PPG sensor circuit;
 - (b) Achieve working circuit using the hardware Seeeduino XIAO;
 - (c) Code in Arduino to acquire the raw PPG signal;
 - (d) Stream the acquired values real-time on Python;
 - (e) Write algorithms to calibrate the raw signal to match the systolic and diastolic pressure values of each subject;
 - (f) Extract final calibrated PPG signal.
3. Testing.
 - (a) Verification if the obtained signal is reliable (with the expected configuration) with the testing in 10 subjects;
 - (b) Analyse the findings.

3. Methodology

This section is dedicated to the explanation of how the PPG circuit was built, and how the post-processing of the signal was done.

3.1 Photoplethysmography Sensor

The PPG sensor circuit was built having the following requirements into consideration.

- A Reflective Optical Sensor with an infrared Light-emitting diode (LED) of 950 nm was used, as it penetrates more deeply, being typically used for acquiring the PPG signal for the measurement of BP [14];
- The frequency of a heartbeat signal is between 0.5 and 4 Hz (30 to 240 BPM) [1], thus other frequencies are filtered;
- The selected measurement site was the finger, which has the strongest evidence of producing accurate BP measurements [5].

In order to measure PPG signals, the sensor should consist of a light emitter and a light detector. The chosen sensor was the TCRT1000 [15], which is a reflective sensor that has both the emitter and the photo transistor in a single component, avoiding the tunable problem of setting the distance between the LED and photo sensor, and providing enclosure inside a leaded package so that there is minimum effect of surrounding visible light [16] [17]. Additionally, the TCRT1000 has an emitter that uses infrared light with a wavelength of 950 nm. A fingertip can be placed over the sensor (usually the pointer) and it will act as the reflector of the light that comes from the built-in emitter. Then, the reflected light from the fingertip will be detected and monitored by the built-in phototransistor.

Circuit design

In figure 3.1, the circuit of the sensor (only) is schematized. The output (V_{sensor}) is a periodic physiological waveform attributed to small variations in the reflected infrared light which is caused by the pulsatile tissue blood volume. The waveform is, therefore, synchronous with the heart beat. In other words, the TCRT1000 sensor converts the fluctuating reflected light intensity into electrical signals (voltages) [4].

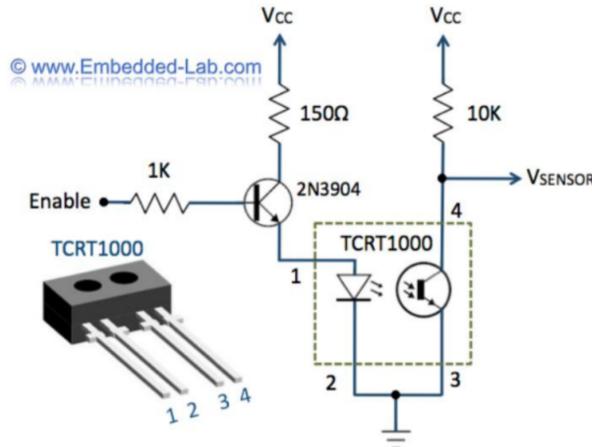


Figure 3.1: Circuit Diagram for the IR emitter and optical sensor **TCRT1000**. [4]

The obtained signal (V_{sensor}) includes both DC and AC components, as mentioned previously. Since the important information lays within the AC component, a **RC high-pass filter** was used to suppress the large DC component and boost the weak pulsatile AC component. (Figure 3.2)

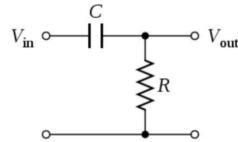


Figure 3.2: RC Hight-Pass Filter. For our circuit, V_{in} is the V_{sensor} previously explained.

The cut-off frequency, given by the expression 3.1, was tuned by selecting the resistor and capacitor values. A **cut-off frequency of 0.72 Hz** will be considered, which can be achieved by setting $R_1 * C_1 = 0.22\Omega F$. By fixing $R_1 = 47k\Omega$, it is obtained $C_1 = 4.7\mu F$.

$$f_s = \frac{1}{2 * \pi * R * C} \quad (3.1)$$

The voltages of the resulting PPG signal are between $1 - 10mV$ [18] [17]. Since the minimum resolution of the electronic boards is limited (e.g. *Arduino Uno* has a resolution of $5mV$), the PPG signal was amplified, with a **gain of 100**, which enabled an appropriate measurement of the signal ($100 - 1000mV$).

Additionally, knowing that the heart rate will have a range between 30 and 240 BPM (or 0.5 and 4 Hz), the signal was also conditioned by a low-pass filter. The amplification and low-pass filtering can be unified in a single stage by an **Active Low-Pass Filter (LPF)**, represented in Figure 3.3, with its transfer function translated in expression 3.2.

$$H(w) = \frac{R_f + j\omega CR_f R + R}{R(j\omega CR_f + 1)} \quad (3.2)$$

In which C is the parallel of both capacitors.

The cut-off frequency (frequency of its pole), given by expression 3.3, can be tuned by selecting the values of the resistor and capacitor in the negative feedback loop. A **cut-off frequency of 4Hz** will be considered, which can be achieved by setting $R_f * C = 0,04\Omega F$. By fixing $R_f = 200k\Omega$, it is obtained $C = 200nF$, which gives approximately the desired cut-off frequency ($f_c = 3.98Hz$). For the gain (A), it is given by $\frac{R_f}{R}$, which should give 100, thus $R = 2k\Omega$.

$$f_c = \frac{1}{2 * \pi * R_f * C} \quad (3.3)$$

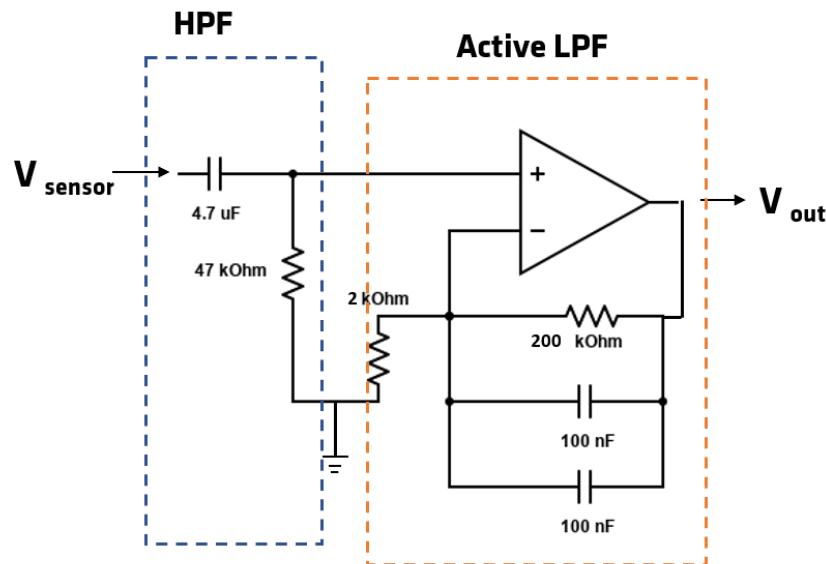


Figure 3.3: First stage of signal conditioning: High pass filter (HPF), previously seen, and Active Low-Pass Filter (LPF) (with an Operational Amplifier (Amp op))

Next, a resistor and a LED (in series) were added to the circuit. The LED will blink if the fingertip is not correctly positioned in the sensor. If the LED stops blinking, then a measurement can be performed. Finally, a non-inverting buffer was added to the circuit to lower the output impedance. The final circuit design can be seen in Figure 3.4.

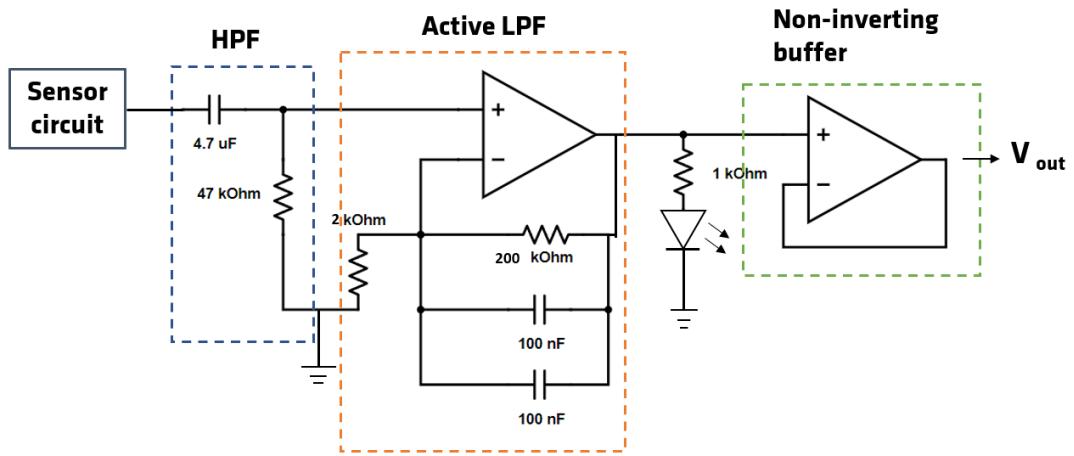


Figure 3.4: Final scheme of the derived circuit. The sensor circuit can be seen in Figure 3.1.

The V_{out} is then connected to an analog input of the Arduino.

3.1.1 Final hardware

The built hardware went through various phases in order to reach the final result we aspired to have.

The final hardware was meant to look as minimalist and easy-to-use as possible.

The first version of the hardware can be seen in Figure 3.5.

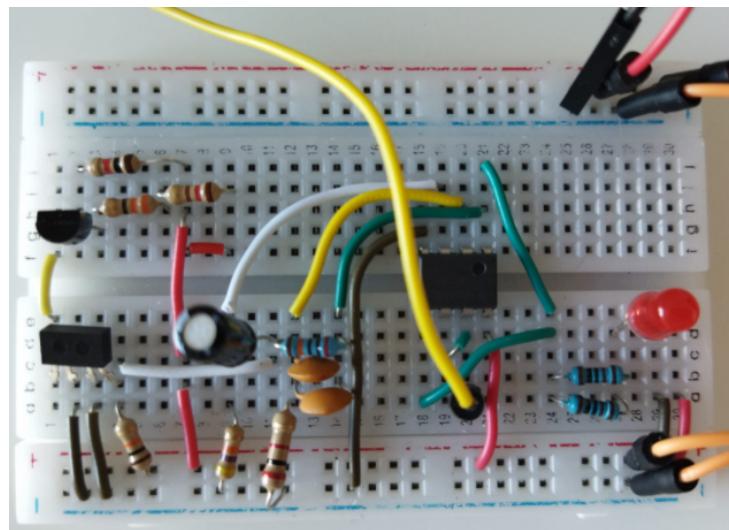


Figure 3.5: First version of the hardware of the PPG sensor circuit.

Then, the same circuit was welded in the following way.

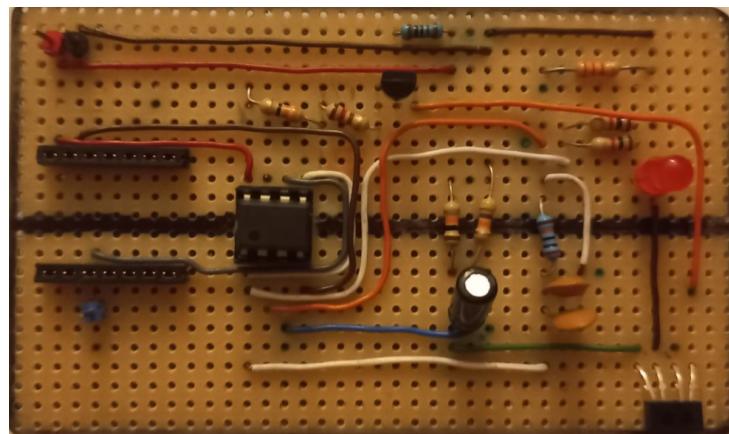


Figure 3.6: Second version of the hardware of the PPG sensor circuit.

Finally, the platform <https://fritzing.org/> was used to create a prototype of the circuit - Printed circuit board (PCB), as seen in Figure 3.7.

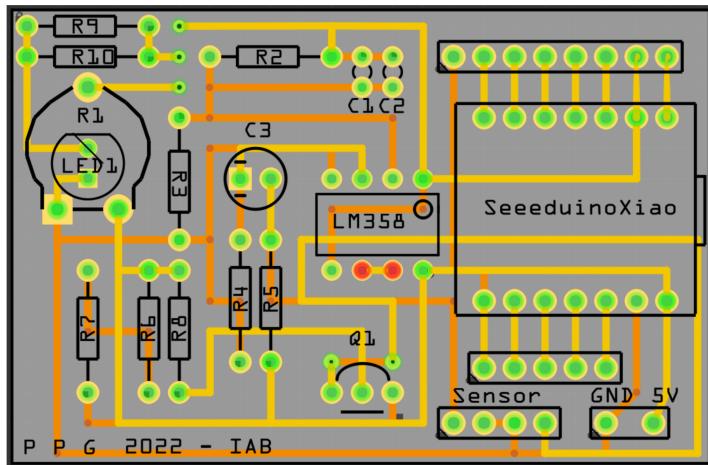


Figure 3.7: Final (prototype) version of the hardware of the PPG sensor circuit.

3.2 Software

A very important portion of this project lies in the developed software. Firstly, a simple Arduino code was written to read the analog values of the described circuit. Additionally, in Arduino, the signal was also sampled with a sampling frequency of 30 Hz, which obeys the sampling theorem. It is important to note that the values streamed through the serial port were the "current" time value (with the help of the function `millis()`) and the analog value read as an input.

The more complex post-processing of the signal was done in Python. After the code in Arduino is uploaded, it was possible to stream the values in Python (using the correct PORT) real-time, with the help of the function `FuncAnimation`.

The developed python code does a calibration of the PPG signal measured for each subject real-time with their previously measured values for the arterial pressure - systolic and diastolic. Next, a step-by-step guide of how the code works is further explained.

Firstly, the **Interface** code must be ran. A user interface appears, which is shown in Figure 3.8.

Calibration

- For each different subject, the user should click on the first button: **Calibrate Sensor**. A new window will open with the real-time raw PPG signal. If the space command is given in the keyboard, the signal starts being recorded to a text file (both time and the analog read). When the space command is given a second time, the recording of the data stops and the window closes. This was done so that the user could choose him/herself an appropriate interval (with a correct signal), in which the subject was placing the fingertip correctly in the sensor. An example of the raw PPG signal is shown in Figure 3.9.

- Then, the obtained values for the subject for the systolic and diastolic pressure should be written in the correspondent entries in the interface. The measurement of the arterial pressure should be per-

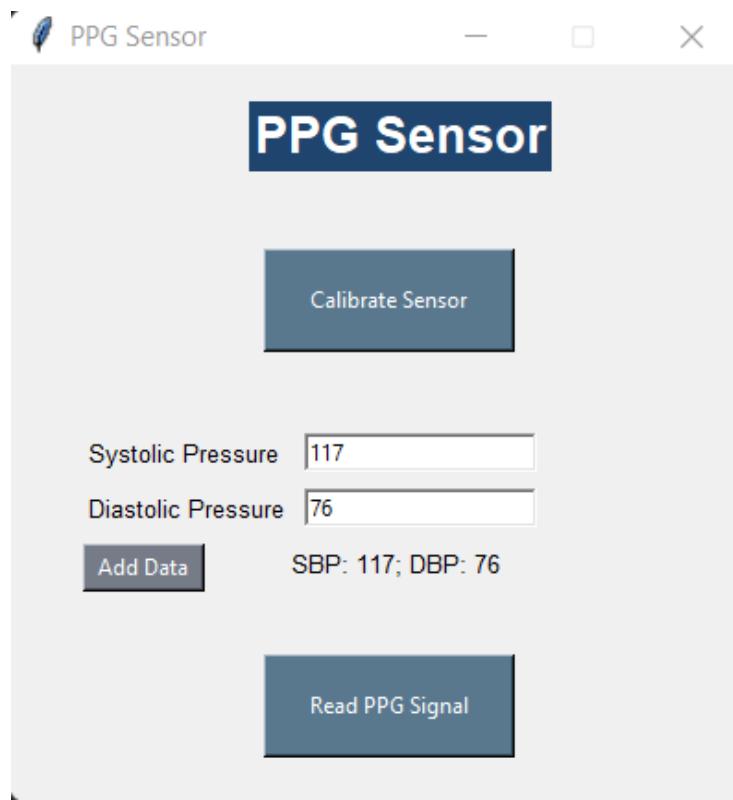


Figure 3.8: User Interface example, with the values of 117 and 76 mmHg taken from a subject.

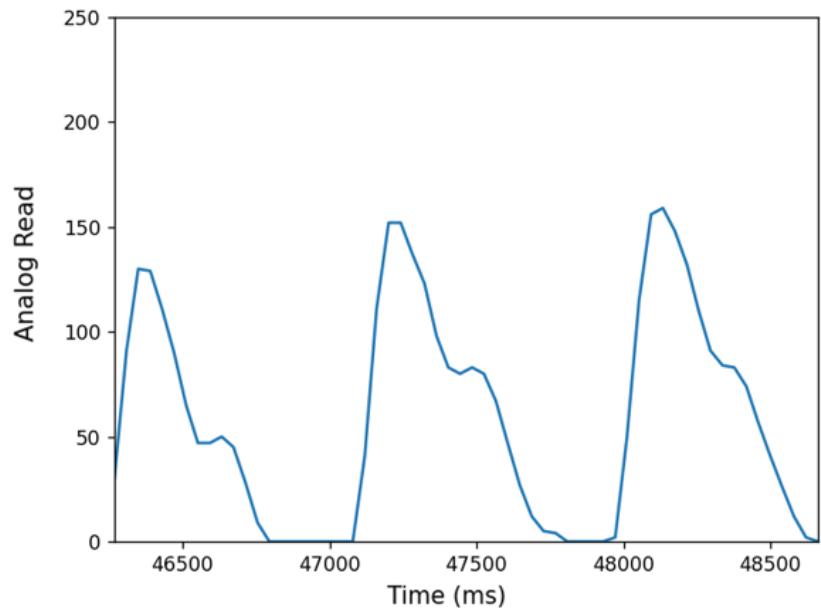


Figure 3.9: Example of the raw PPG signal. The minimum value is approximately 0, and the maximums are approximately 150.

formed in a short time period before the experiment starts. It is to note there are no units in the pressure in the interface, since the user can choose in which units they want to perform the calibration with. Here, the given diastolic and systolic pressure are used as a global variable, which is the input of a created function `calib`, that performs the pretended calibration.

3. After the user clicks on **Add data**, the function `calib` is used for the added pressure data, as its input. This function calculates the difference between the maximum and the minimum of the PPG signal and multiplies it by a scaling factor that relates this difference to the difference of the read systolic and diastolic pressure. It also subtracts the signal from the raw signal's minimum values and adds the read diastolic pressure (the "new" minimum) (see equation 3.4). This process allows the scaling of the obtained raw signal to the systolic and diastolic pressure of each subject. Next, a brief explanation of how this is achieved is given.

$$y_{scaled} = (y_{raw} - y_{min}) * f + d \quad (3.4)$$

Where f is the scaling factor and d is the measured diastolic pressure.

Firstly, the `calib` function takes the calibration data recorded from the text file, and calculates the relative maximums and minimums of the PPG signal, storing them in a `numpy` array. Then, the variable `threshold` is created, which will be auxiliary in representing a range of values where the maximums and minimums should not be considered. This prevents the detection of unwanted peaks caused by noise. This `threshold` is merely the average value between the absolute maximum and absolute minimum. Then, the maximums that are actually chosen (that are meant to be the absolute maximum of each peak of the PPG) are the ones above the sum of the `threshold` with the coefficient $(y.\max() - y.\min())*0.3$. The minimums chosen are the ones bellow $\text{threshold} - (y.\max() - y.\min())*0.3$. After having the mean of the new maximums and minimums, the difference between them is taken as a new variable `exp_dif` (experimental difference). The scaling factor will then be the fraction between the difference of the measured systolic and diastolic pressure and the `exp_dif`. The next Figure 3.10 is an example of the graph that pops up after the user has clicked on **Add data**. It is important to emphasize that the interval of values captured of the raw PPG signal was the previously chosen by the user, therefore it can be as large or as small as the user desires, but keeping in mind that higher amount of information acquired results in more precise results for the calibration.

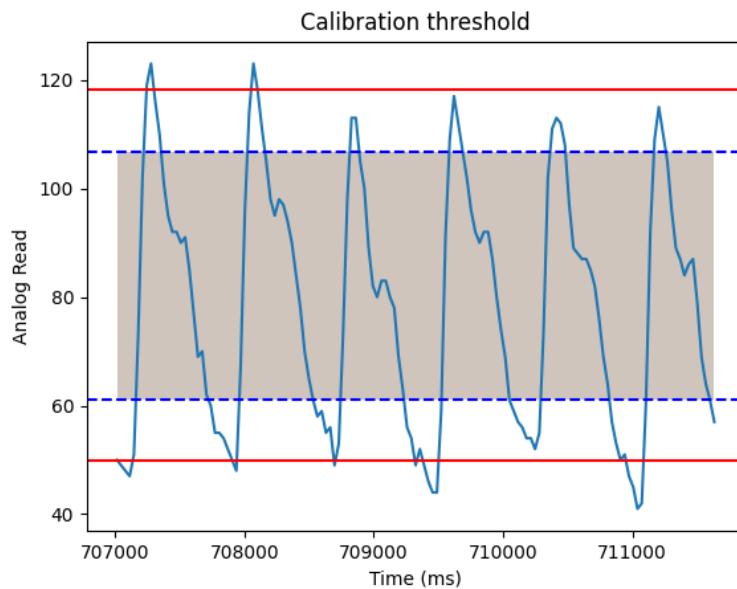


Figure 3.10: Graph that pops up after the user adds the measured data of the systolic and diastolic pressure of a subject. The blue dashed lines represent the threshold in which the relative maximums and minimums were ignored. The red lines represent the mean of the absolute maximums and minimums.

Then, a Message box is shown to the user, with the value of the scaling factor for the subject, as shown in Figure 3.11. Additionally, all relevant scaling data (measured diastolic and systolic pressure and scaling factor) are saved in a csv file.

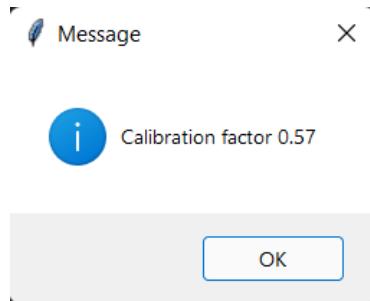


Figure 3.11: Message pop-up with the calibration factor of one subject.

In the following pages, the devised code for the function `calib` is shown.

```

1 import numpy as np
2 from scipy.signal import argrelextrema
3 import matplotlib.pyplot as plt
4 from pathlib import Path
5
6
7 def calib(sis_press, dias_press):
8     x = np.zeros(0)
9     y= np.zeros(0)
10    ymin_mean = 0
11
12    file_data = np.loadtxt("calib_data.txt", dtype='str')
13    for i in file_data:
14        l = i.split(',')
15        x = np.append(x, float(l[0]))
16        y = np.append(y, float(l[1]))
17
18    maximo = argrelextrema(y, np.greater)[0]
19    minimo = argrelextrema(y, np.less)[0]
20
21    y_max = np.zeros(0)
22    y_min = np.zeros(0)
23
24    for i in maximo:
25        y_max = np.append(y_max, y[i])
26
27    for j in minimo:
28        y_min = np.append(y_min, y[j])
29
30    threshold = (y_max.max() + y_min.min()) / 2
31    coef_threshold = (y_max.max() - y_min.min())*0.3
32
33    f_ymax = y_max
34    f_xmax = maximo
35
36    for i in range(len(maximo) - 1, -1, -1):
37        if (y_max[i] <= threshold + coef_threshold):
38            f_ymax = np.delete(f_ymax, i)

```

```

39         f_xmax = np.delete(f_xmax, i)
40
41     f_ymin = y_min
42     f_xmin = minimo
43     for i in range(len(minimo) - 1, -1, -1):
44         if (y_min[i] >= threshold - coef_threshold):
45             f_ymin = np.delete(f_ymin, i)
46             f_xmin = np.delete(f_xmin, i)
47
48     exp_dif = f_ymax.mean() - f_ymin.mean()
49     ymin_mean = f_ymin.mean()
50     pres_dif = float(sis_press - dias_press)
51     new_factor = pres_dif / exp_dif
52     print(coef_threshold)
53     print(threshold)
54     print(exp_dif)
55
56     plt.plot(x,y)
57     plt.title('Calibration threshold')
58     plt.xlabel('Time (ms)')
59     plt.ylabel('Analog Read')
60     plt.axhline(y= f_ymax.mean(), color='r', linestyle='--')
61     plt.axhline(y=(threshold - coef_threshold), color='b', linestyle='--')
62     plt.axhline(y=(threshold + coef_threshold), color='b', linestyle='--')
63     my_plot = plt.fill_between(x, y1=(threshold - coef_threshold), y2=(threshold + coef_threshold))
64     plt.setp(my_plot, facecolor="#614126")
65     plt.axhline(y=f_ymin.mean(), color='r', linestyle='--')
66
67     newPathBoolean = False
68     try:
69         i=0
70         while (not newPathBoolean):
71             new_path = f'calibration{i}.png'
72             image_path = Path(new_path)
73             if image_path.exists():
74                 i+=1
75             else:
76                 newPathBoolean=True

```

```

77         print(f'Image {new_path} was saved')
78
79     except:
80         print('not possible to save image')
81     plt.savefig(new_path)
82     plt.show()
83
84 return new_factor, dias_press, ymin_mean

```

Final Data Acquisition

Next, in the Interface, when the user clicks on **Read PPG signal**, the real-time animation of the PPG signal calibrated for the subject's systolic and diastolic pressure is shown. An example of the obtained graph is shown in Figure 3.12.

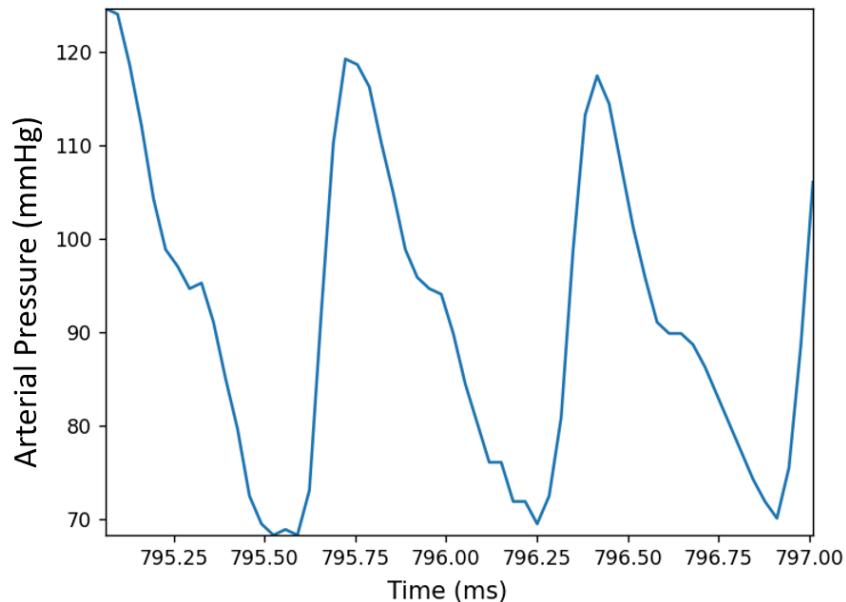


Figure 3.12: Acquired calibrated data from a subject. The minimum value is approximately 70 and the maximum 120. For this subject, a systolic pressure of 117 and diastolic pressure of 76 mmHg were previously measured.

3.2.1 Block diagram

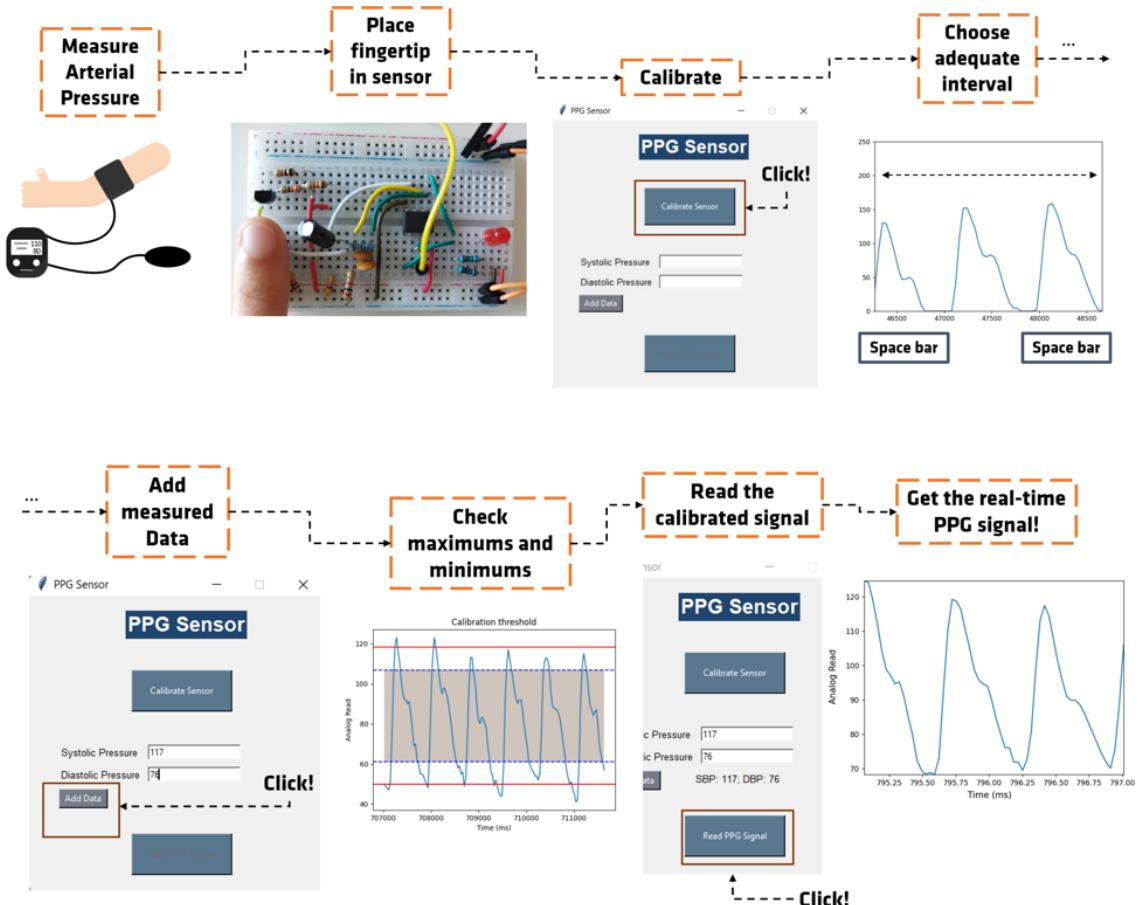


Figure 3.13: Block diagram with step-by-step data acquisition.

3.3 Testing

In order to test the system, the procedure schematized in the previous block diagram 3.13 was performed in 12 subjects.

For the 12 subjects, the same circuit was used and the subject stayed sit with their arm rested in a table and with the fingertip on top of the sensor. The subject was asked not to move or talk.

3.4 Materials

Resistors: 150Ω , $1k\Omega$, $2k\Omega$ $10k\Omega$, $47k\Omega$, $200k\Omega$

Capacitors: $4.7F$, $100nF$ (2)

Transistors: Bipolar - 2N3904

Operational Amplifier: LM358 AmpOp

Sensors: TCRT1000

Other electronic components: micro-controller - Seeeduino XIAO, Breadboard, Jump wires

3.5 Expected Impact

Given the advances in electronics and its commercial availability, it was possible to build a prototype of a single-site PPG sensor for BP real-time monitoring in a short amount of time. In comparison with well-established methods, this constitutes a more feasible solution for continuous monitoring, with this preliminary device being possible to be built into a wearable system.

Regarding the reliability and accuracy of the prototype, it doesn't provide an exact estimation of the BP. Nevertheless, it provides data upon which detection of normal and abnormal BP could be done, by proper algorithms, which in the context of preventive healthcare is a valuable information.

4. Results and Discussion

The results for each subject can be seen in Table 4.1. Additionally, the obtained PPG signal for each subject during calibration can be seen in Appendix A.

Table 4.1: Obtained results of a total of 12 subjects.

Subject	Systolic Pressure (mmHg)	Diastolic Pressure (mmHg)	Calibration factor	Grade
1	117	76	0.60	2
2	91	57	0.26	2
3	131	84	1.21	0
4	101	54	0.70	1
5	106	80	0.39	2
6	100	60	0.44	2
7	119	80	0.76	2
8	102	69	0.45	2
9	150	87	2.17	2
10	125	82	0.41	1
11	110	70	0.32	2
12	121	80	0.34	2

Firstly, it is important to verify if the measured PPG signal is correct and accurate, meaning that if it is possible to differentiate a periodic systolic and diastolic peak, as seen in literature. In order to grade the efficacy of the system in showing correct PPG signals to various patients, the following grading system was adopted: **0** for when there is no periodicity, **1** for when the systolic peak is visible, **2** for when both the systolic and diastolic peaks are visible.

From Table 4.1, it is possible to conclude that 75 % of the obtained PPG waves presented the expected form, which is a visible systolic and diastolic peak.

The discussion about the accuracy of the conceived device is still very limited, since a very reduced sample of subjects was tested, neither a comparison with standard devices was performed. In the future, this should be done, taking into consideration the requirements that a BP measurement method should meet. These criteria were defined by the American National Standards of the Association for the Advancement of Medical Instrumentation (AAMI), which set a maximal error of 5 ± 8 mmHg and a minimum number of subjects tested of 85 [13] [19].

Given the obtained results, it is important to consider some critical aspects that may compromise the performance of the device. Regarding the measurement site, the contact force between the sensor and the finger is hard to control, potentially giving rise to pressure disturbances, which deform the arterial geometry by compression and, consequently, affects the AC amplitude, reducing the BP estimation accuracy [12] [20]. Besides the applied external pressure, the PPG signal amplitude critically depends as well on the hydrostatic pressure, determined by the relative height of the PPG measurement site

with respect to the heart [3]. As for the experimental conditions at which the acquisition was performed, cold environments and bright lights impairs the readings, since cold promotes vasoconstriction (reduced arterial perfusion), making it difficult to distinguish the real signal apart from noise, and the bright lights interfere with the sensor [21]. Finally, since the PPG waveform is influenced by the cardiovascular, respiratory and autonomic systems, the correlation between peripheral pulsation and BP may not be optimal, being necessary a deeper understanding of the morphology and underlying physiology of the PPG signal [12] [19].

A. Results

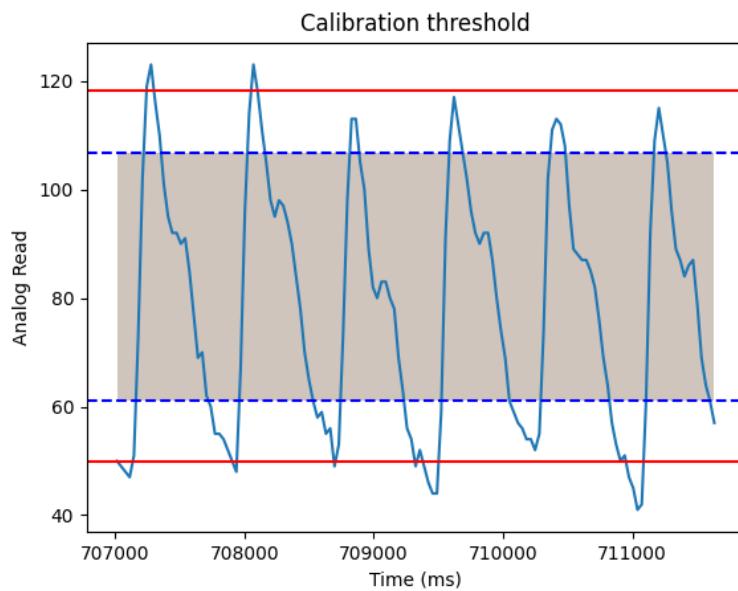


Figure A.1: Results of subject 1.

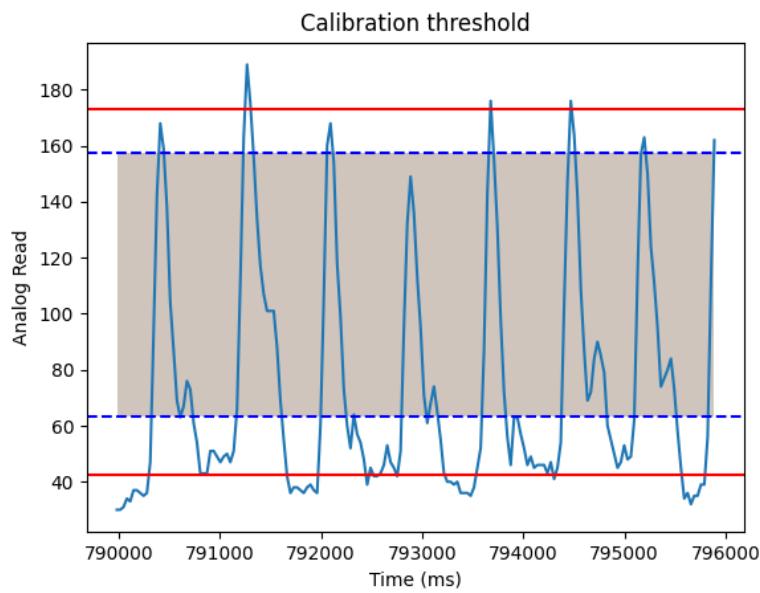


Figure A.2: Results of subject 2.

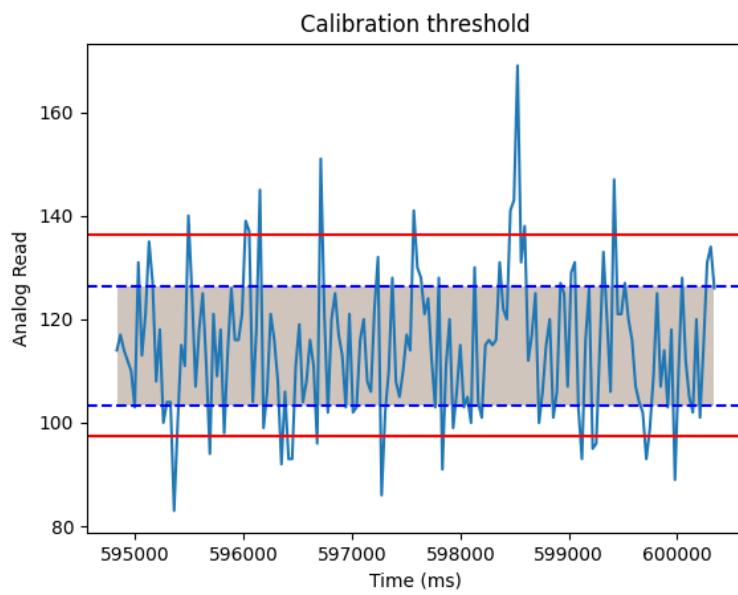


Figure A.3: Results of subject 3.

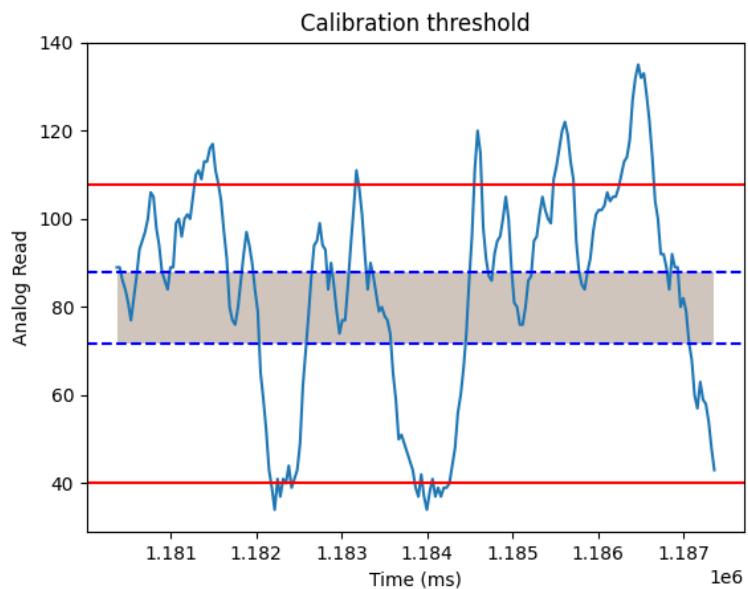


Figure A.4: Results of subject 4.

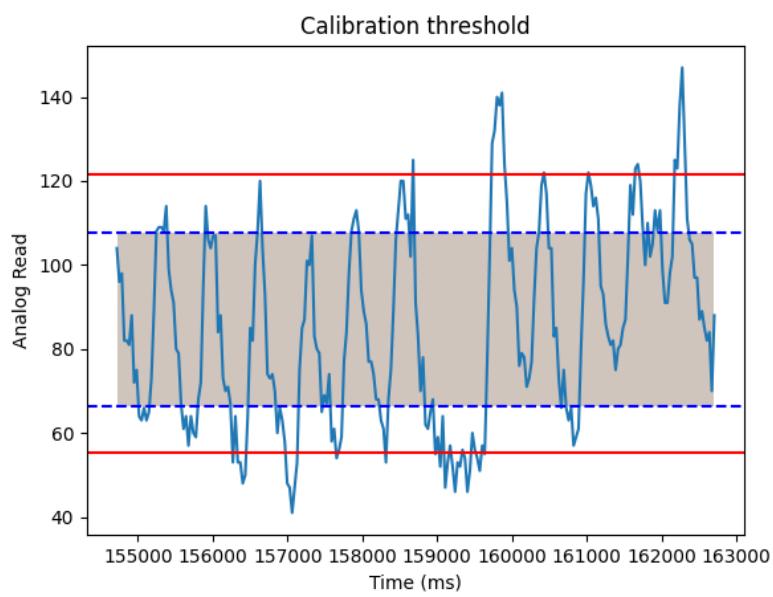


Figure A.5: Results of subject 5.

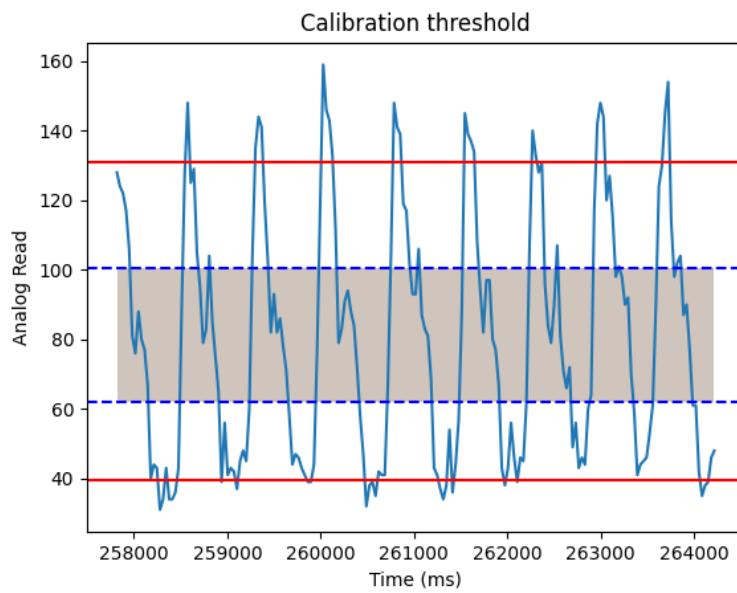


Figure A.6: Results of subject 6.

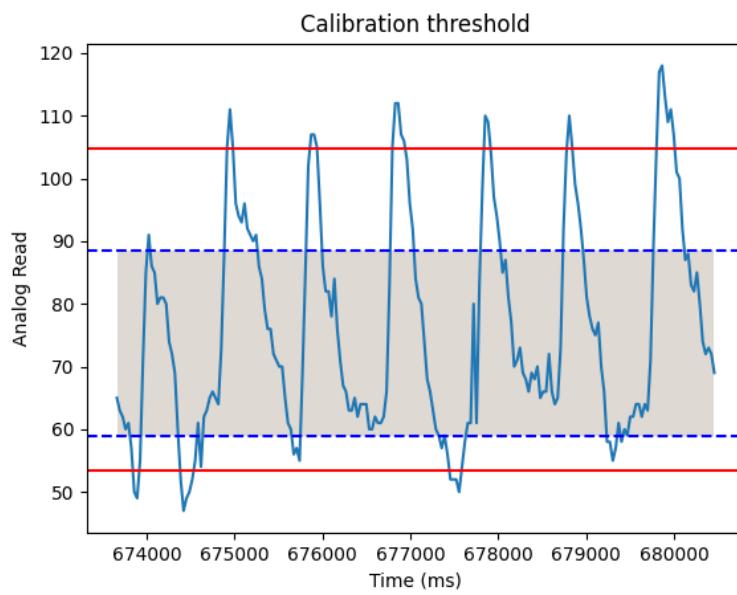


Figure A.7: Results of subject 7.

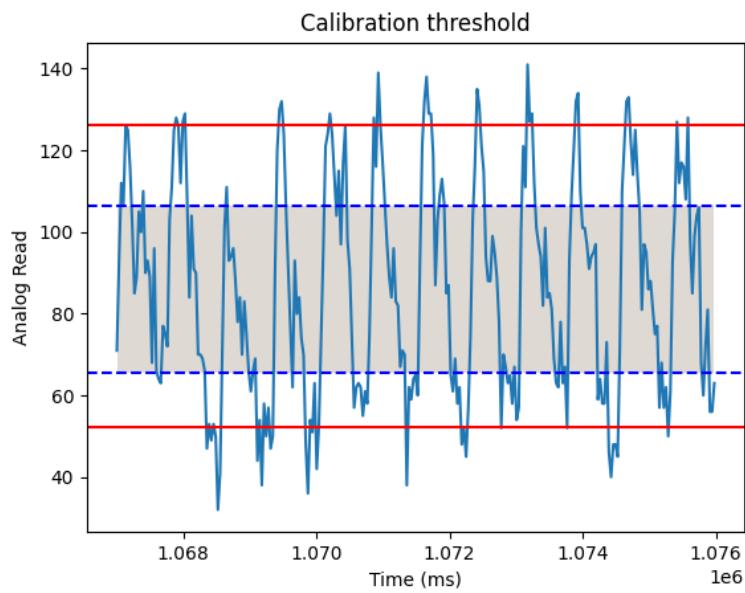


Figure A.8: Results of subject 8.

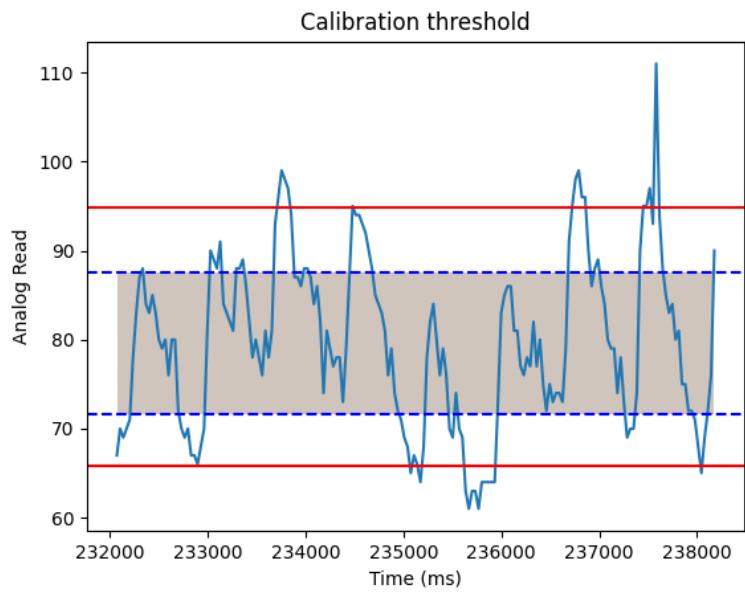


Figure A.9: Results of subject 9.

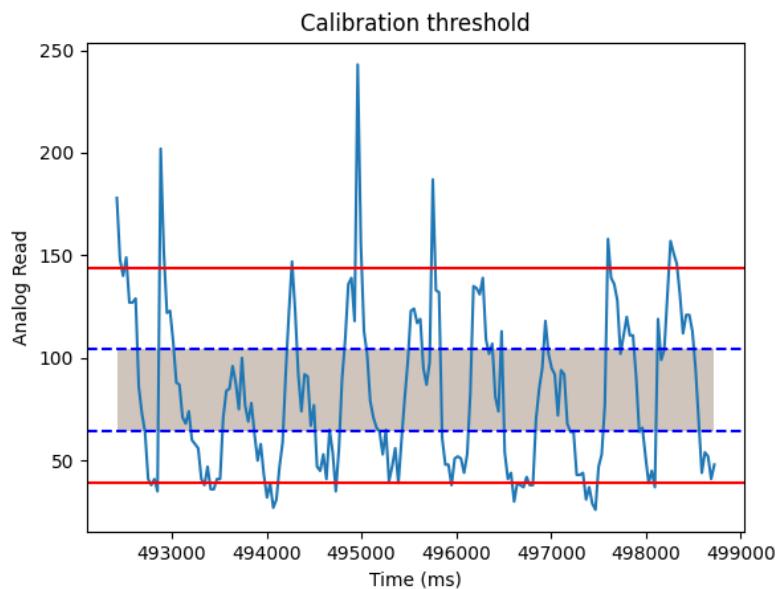


Figure A.10: Results of subject 10.

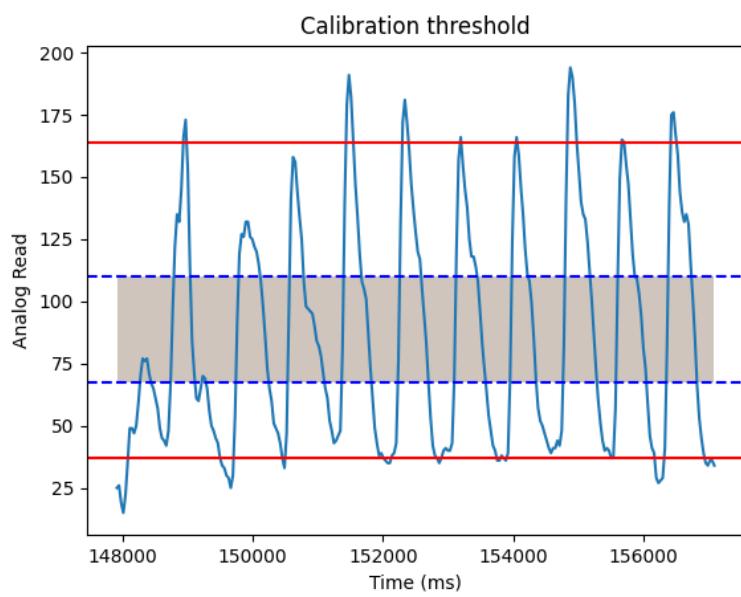


Figure A.11: Results of subject 11.

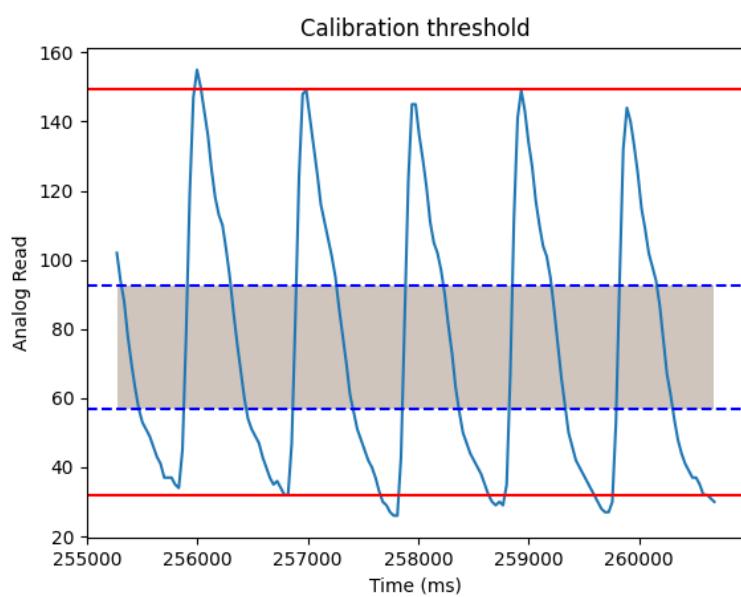


Figure A.12: Results of subject 12.

Bibliography

- [1] J. L. Moraes, M. X. Rocha, G. G. Vasconcelos, J. E. Vasconcelos Filho, V. H. C. de Albuquerque, and A. R. Alexandria, "Advances in photoplethysmography signal analysis for biomedical applications," *Sensors (Switzerland)*, vol. 18, no. 6, pp. 1–26, 2018.
- [2] M. M. P., N. V., and V. J.C., "Spot and continuous monitoring of heart rate by combining time and frequency domain analysis of photoplethysmographic signals at rest conditions," *IET Signal Processing*, vol. 11, no. 9, pp. 1076–1082, dec 2017. [Online]. Available: <https://doi.org/10.1049/iet-spr.2016.0455>
- [3] M. Elgendi, R. Fletcher, Y. Liang, N. Howard, N. H. Lovell, D. Abbott, K. Lim, and R. Ward, "The use of photoplethysmography for assessing hypertension," *npj Digital Medicine*, vol. 2, no. 1, p. 60, 2019. [Online]. Available: <https://doi.org/10.1038/s41746-019-0136-7>
- [4] "Introducing Easy Pulse: A DIY photoplethysmographic sensor for measuring heart rate." [Online]. Available: <https://embedded-lab.com/blog/introducing-easy-pulse-a-diy-photoplethysmographic-sensor-for-measuring-heart-rate/>
- [5] M. Hosanee, G. Chan, K. Welykholowa, R. Cooper, P. A. Kyriacou, D. Zheng, J. Allen, D. Abbott, C. Menon, N. H. Lovell, N. Howard, W.-S. Chan, K. Lim, R. Fletcher, R. Ward, and M. Elgendi, "Cuffless Single-Site Photoplethysmography for Blood Pressure Monitoring," *Journal of clinical medicine*, vol. 9, no. 3, p. 723, mar 2020. [Online]. Available: <https://pubmed.ncbi.nlm.nih.gov/32155976>
- [6] R. Lazazzera, Y. Belhaj, and G. Carrault, "A New Wearable Device for Blood Pressure Estimation Using Photoplethysmogram," *Sensors (Basel, Switzerland)*, vol. 19, no. 11, p. 2557, jun 2019. [Online]. Available: <https://pubmed.ncbi.nlm.nih.gov/31167514>
- [7] T. Nagasawa, K. Iuchi, R. Takahashi, M. Tsunomura, R. P. de Souza, K. Ogawa-Ochiai, N. Tsumura, and G. C. Cardoso, "Blood Pressure Estimation by Photoplethysmogram Decomposition into Hyperbolic Secant Waves," 2022.

- [8] I. f. Q. (IQWiG) and E. in Health Care, "What is blood pressure and how is it measured?" [Online]. Available: <https://www.ncbi.nlm.nih.gov/books/NBK279251/>
- [9] G. Slapničar, N. Mlakar, and M. Luštrek, "Blood Pressure Estimation from Photoplethysmogram Using a Spectro-Temporal Deep Neural Network," *Sensors (Basel, Switzerland)*, vol. 19, no. 15, p. 3420, aug 2019. [Online]. Available: <https://pubmed.ncbi.nlm.nih.gov/31382703>
- [10] F. Riaz, M. A. Azad, J. Arshad, M. Imran, A. Hassan, and S. Rehman, "Pervasive blood pressure monitoring using Photoplethysmogram (PPG) sensor," *Future Generation Computer Systems*, vol. 98, pp. 120–130, 2019.
- [11] Á. Solé Morillo, J. Lambert Cause, V. E. Baciu, B. da Silva, J. C. Garcia-Naranjo, and J. Stiens, "PPG EduKit: An Adjustable Photoplethysmography Evaluation System for Educational Activities," *Sensors*, vol. 22, no. 4, pp. 1–22, 2022.
- [12] X. Xing, Z. Ma, M. Zhang, Y. Zhou, W. Dong, and M. Song, "An Unobtrusive and Calibration-free Blood Pressure Estimation Method using Photoplethysmography and Biometrics," *Scientific Reports*, vol. 9, no. 1, pp. 1–8, 2019. [Online]. Available: <http://dx.doi.org/10.1038/s41598-019-45175-2>
- [13] N. Hasanzadeh, M. M. Ahmadi, and H. Mohammadzade, "Blood Pressure Estimation Using Photoplethysmogram Signal and Its Morphological Features," *IEEE Sensors Journal*, vol. 20, no. 8, pp. 4300–4310, 2020. [Online]. Available: <https://doi.org/10.1109/JSEN.2019.2961411>
- [14] M. H. Chowdhury, M. N. I. Shuzan, M. E. H. Chowdhury, Z. B. Mahbub, M. M. Uddin, A. Khandakar, and M. B. I. Reaz, "Estimating Blood Pressure from the Photoplethysmogram Signal and Demographic Features Using Machine Learning Techniques," *Sensors (Basel, Switzerland)*, vol. 20, no. 11, p. 3127, jun 2020. [Online]. Available: <https://pubmed.ncbi.nlm.nih.gov/32492902>
- [15] PTRobotics. (2022) PC robotics, TCRT1000 - Reflective Optical Sensor with Transistor Output. Accessed 27-March-2022. [Online]. Available: <https://www.ptrobotics.com/sensores-infravermelho/4328-tcrt1000-reflective-optical-sensor-with-transistor-output.html>
- [16] G. R. Patancheru, *A wearable prototype of reflective sensor for non invasive measurement of heart rate.*
- [17] JuneYoung Kim, F. Advisor, and L. Beaty, "Design of Infrared Sensor Based Measurement System for Continuous Blood Pressure Monitoring Device."
- [18] N. Hossain, S. Sharmin, and N. Nasir, "Heart Rate Measurement Through Photoplethysmography," pp. 1–17, 2014.

- [19] X. Xing and M. Sun, "Optical blood pressure estimation with photoplethysmography and FFT-based neural networks," *Biomedical optics express*, vol. 7, no. 8, pp. 3007–3020, jul 2016. [Online]. Available: <https://pubmed.ncbi.nlm.nih.gov/27570693>
- [20] T. Tamura, "Current progress of photoplethysmography and SPO(2) for health monitoring." *Biomedical engineering letters*, vol. 9, no. 1, pp. 21–36, feb 2019.
- [21] M. Nitzan, A. Romem, and R. Koppel, "Pulse oximetry: fundamentals and technology update." *Medical devices (Auckland, N.Z.)*, vol. 7, pp. 231–239, 2014.