Heart rate measurement through PPG

Heartbeat measurement in a wireless headset

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Challenge the future

HEART RATE MEASUREMENT THROUGH PPG

HEARTBEAT MEASUREMENT IN A WIRELESS HEADSET

by

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in partial fulfillment of the requirements for the degree of

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This thesis is confidential and cannot be made public until July 1st, 2015.

PREFACE

This thesis serves as a conclusion to the Bachelor Graduation Project, a part of the Electrical Engineering Bachelor at the Delft University of Technology (TU Delft). This project is the final chapter of a three year curriculum and has to be concluded successfully to be admitted to a master course. The project spanned the period from the 20th of April 2015 to the 3rd of July.

The proposal of this research topic was done by Dr. Ir. G. de Graaf in collaboration with Plantronics®. This research topic was explored with a team of six members. The research consisted of the development of a heart rate sensor that can be implemented into a wireless headset, the BackBeat FIT [1]. In discussion with Plantronics®, the research topic was slightly modified in the way that it was shifted towards different techniques that could be used to measure the heart rate. The prototype did not have to be implemented in the wireless headset. During this project, experience was gained in project management and technical expertise.

We would like to thank our supervisor Dr. Ir. Ger de Graaf and technical supervisor Ing. Ron van Puffelen for their supervision during this project. They were essential in providing us with knowledge and hardware. We would also like to thank Plantronics® for the opportunity to work on this research topic, and providing us with some of their BackBeat FIT models.

A big thanks goes out to our fellow group members D.C. Kaandorp, A.I. Kanhai, J.A.G Jonkman, and T.M de Rijk for their help and judgement during this project, and of course for the fun and cheerful work atmosphere.

ABSTRACT

This thesis, assigned by Plantronics®, proposes a solution to the motion artifacts that corrupt the results of PPG (Photo Plethysmo Graphic) signals and therefore the determined heart rate during physical exercises. An Infra-Red light emitting diode and phototransistor package was used to create a PPG signal that was amplified using an operational amplifier and filtered using a high pass and low pass filter. Research was done on PPG signals corrupted by motion with the help of an accelerometer. The fast Fourier transform of the signals showed that there is a relation between the frequency components of the PPG signal and motion signals. Based on this finding a working filter was designed in MATLAB that compares the frequency spectrum of the PPG to motion signals and removes any overlap. The experimental results for running motions prove the correct functioning of this system and showed that invasive sensing techniques are unnecessary.

INTRODUCTION

In this age of gadgets and smart devices, manufacturers try to add as many features to a device as possible. Well known examples are smartphones, but smartwatches are also on the rise, as are many other devices like smart glasses and earphones.
Another trend is seen in a different sector: sports. With all the new smart devices and their ability to track via GPS, a rise in physical activity is observed. While some people are competitive against their friends, others just want to be able to check their progress or post their results on social media. There is one element that lacks in most smart sports devices: audio. Of course it would be anti-social to use the smart devices' speakers and let the public enjoy your music, so the common solution is to use earphones or a headset. To solve the complication of wires around the head, wireless headsets were invented, such as the BackBeat FIT [1] by Plantronics® [2], which can be seen in Appendix A. To combine the sports and new smart gadgets, Plantronics® proposed to make an addition to the BackBeat FIT. Not only is it able to stream music from one's smart device and able to accept calls, it will also be capable to measure the heart rate and display this on the smart device. It will also be possible to get live audio feedback by pressing a button on the headset.

Together with four other teammates, research was done about different methods of heartbeat detection, keeping in mind that the measuring location is in or around the ear. Three different methods arose:

- Temperature based measurement
- Skin discolouration detection
- Photoplethysmography (PPG)

For this thesis, the latter method was thoroughly researched and the results are described in the following chapters.
This thesis has multiple goals. The first goal is to design and implement a small wearable PPG device. The second goal is to investigate the effect of motion artifacts on the PPG signal. The third and final goal of this thesis is to find a solution for the motion artifact problem.

ABBREVIATIONS

- ANC - Adaptive Noise Canceling
- BPM - Beats per minute
- DC - Direct Current
- FFT - Fast Fourier Transform
- GUI - Graphical User Interface
- IC - Integrated Circuit
- IR - Infrared
- LED - Light emitting diode
- LMS - Least Mean Square
- LPF - Low pass filter
- LxWxH - Length x Width x Height
- PPG - Photoplethysmography
- RLS - Recursive Least Square

CONTENTS

1

ETHICAL ASPECTS

When making heart rate sensors, it is important to keep in mind that one is working with personal and sensitive data, which can be of great value to certain parties. In this chapter several ethical problems that arise when working with such data will be discussed.

Although PPG sensors are able to measure heart rates below 30 BPM and above 230 BPM, all that data will not be displayed by our system (see chapter 6 for more information). This means that, even though it is capable of measuring it, the heart rate will not be displayed during a cardiac arrest for example. According to the principle of care ethics we should display this information to help the public during these critical situations. It is, however, our professional opinion that this sensor cannot measure the heart rate with a medical reliability. This information should therefore not be used during situations where the result is used as a reference for medical decisions.

On top of that, one can also look at the ethical questions that arise when insurance companies are involved. Data such as heart rate can tell a lot about one's health and can thus be of great value to such parties. If one sells heart rate information to an insurer, they could alter their policies or premiums on a per-person basis. According to the utilitarianism selling this kind of information would be a sound option as the insurers would have more information to personalize a policy or premium, and people with a healthy lifestyle, and thus less insurance claims, will not have to pay for claims from people with an unhealthy lifestyle. Furthermore, the selling of this information might encourage people to live a healthy lifestyle, as living such a lifestyle would then be associated with a reduced insurance premium.

However, bringing the data from continued heart rate monitoring to insurance companies is something new, which would bring us in the domain of responsibility ethics. The seller of the information and the insurance companies would get a vacant responsibility. Vacant responsibilities are when no responsible party can be successfully identified. This is due to there being no current rules for the utilization of this information. There is currently no situation in which continuous heart rate measurement penalizes people on their insurance policy.

2

RELEVANT RESEARCH

New ways of accurately determining the human heart rate are investigated by research groups all over the world. Colleagues from the Delft University of Technology are researching the determination of the heart rate through skin discolouration [3] and other colleagues are looking at heart rate measurements by measuring temperature fluctuations caused by heartbeats [4]. Even though photoplethysmographic (PPG) is not a new technology, researchers are still trying to improve one of the main problems with this technique: motion artifacts [5] [6] [7]. PPG also has other problems. This will be covered in Chapter 3.

The goal of Plantronics® is to implement a heart rate sensor into a wireless headset. Therefore the best location for heart rate measurements in and around the ear needs to be determined. Other researchers have looked at the determination of heart rates in the ear [8] [9] as well as the anatomy of the ear and its surroundings in general [10] [11] [12].

Researchers at Plantronics® have also looked at the detection of heart rates at the ear. During a meeting they showed several concepts and explained the need for further research. Their biggest problem was the occurrence of motion artifacts during physical exercise. They suggested a research exploring several new ways of heart rate detection and to investigate techniques to filter motion artifacts without using invasive sensors.

3

THEORY

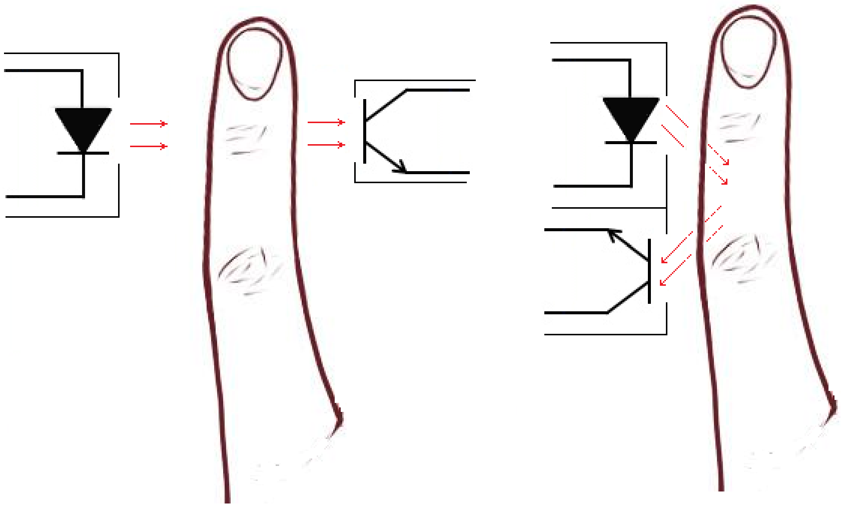
3.1. PHOTOPLETHYSMOGRAPHY

Photoplethysmography or PPG is a technique to measure the heartbeat that uses the ability of light to reflect and penetrate in human tissue. With every pulse the blood vessels increase in thickness and the body will therefore absorb more light as the light will have to travel through more tissue. PPG detects volumetric changes in arterial vessels that cause a change in the light absorption, reflection and therefore the light intensity detected by the photodetector [13].

In most cases the measurement system consists of a LED, a photodetector and an electric system to filter and amplify the signal. What wavelength of light works best for a certain application is dependent on the type of tissue on which it will be used [14].

PPG heartbeat measurement can be done through two different methods:

- Light transmission measurements
- Light reflection measurements



(a) Schematic picture of transmission PPG

(b) Schematic picture of reflection PPG

Figure 3.1: Two different methods for PPG

TRANSMISSION PPG

In the case of light transmission measurements, light is transmitted through a medium, and detected on the opposite side. This is presented in figure 3.1a. Transmission PPG is currently used in finger tip heart rate monitors that can be found in most hospitals. This technology is also used on the ear lobe [8][15][16][17].

REFLECTION PPG

The other method is reflection PPG. This involves the reflection of light on a particular medium. Due to the measurement being done on the ear, and the invasiveness of the standard transmission PPG earlobe clip, the choice for reflection PPG is appropriate. As can be seen in figure 3.1b, the sensor would be flat on the skin on only one side, compared to both sides for transmission PPG. The reflective PPG can be done on the inner ear or on the mastoid area behind the ear. This is best done through a micro-optic remission/reflection sensor [9].

The analysis of the PPG signal may be the most important part of the monitor, because it needs to extract the heartbeat signal from the raw data, which includes a lot of ambient noise and motion artifacts [18][19][20].

PPG has a few limitations that limit the quality of the signal. There are different factors that influence the measured reflection and the possibility to filter the heartbeat.

- No other absorber exists for the measurement other than the arterial blood. However skin, bone, tissue and venous blood streams enhances the noise levels[21].
- It has a relatively large DC component compared to actual PPG signal. A reduced blood level in the limbs can cause this signal to be undetectable[22].
- Ambient light susceptibility. The sensors typically used are a combination of an emitter and a photo detector. The photo detector is affected by ambient light. A solution for this could be to use a form of shielding, or to measure the ambient light and subtract this from the PPG signal.
- Motion artifacts. Motion causes changes in the reflected light received by the photo detector. This is the most important problem for reflection PPG. A small change in the reflected light will result in inaccurate measurements.

3.2. HEART RATE CALCULATION

Two methods arise to determine the heart rate out of the PPG signal. The first method is based on the determination of the peaks of the heartbeats and the interval between them. This gives the period of the heartbeat signal. Thus the reciprocal is the heart rate. The second method lies in the determination of the heart rate through a fast Fourier transform (FFT). In the FFT the heart rate can be seen as a large spike at the frequency of the heart rate.

When a PPG sensor is used during exercise, the heart beat signal might be polluted in such a way that regular signal processing tools can not derive the heart rate. The main reason that this causes problems for the signal analysis is, that the motion can be in the same frequency range as the heart rate signal, normally between the 0.5 and 4 Hz [23] [24]. Motions that occur during exercise are in the same bandwidth and range from 1 to 2 Hz. Therefore common filtering methods will not work.

In order to determine the motion that corrupts the heart beat measurement, it has to be measured. There are several methods to measure motion, but use of an accelerometer is in this case the most promising one. Accelerometers are often used to provide a motion reference for adaptive noise cancellation [25][26].

Adaptive noise cancellation is done through the use of an adaptive filter. An adaptive filter is different from a fixed filter in the way that the impulse response can be adjusted depending on the filter's output. With the correct algorithm the filter can operate under changing conditions, readjusting itself to minimize the error signal. [7].

4

SENSOR SYSTEM

As mentioned before, heartbeats can be measured using a micro-optic reflection sensor [9]. In this section the requirements are set for the heartbeat sensor and on the basis of these requirements a design is made for the heartbeat measurement circuit. This circuit is then simulated and tested using different sensors, after which a comparison is made. Furthermore, the system in total will first be tested on the finger to ensure correct functionality. The system is then tested on several locations around the ear. These locations include the mastoid area, the earlobe and, finally in the auditory canal.

4.1. REQUIREMENTS

The heartbeat measurement circuit has the following requirements:

4.1.1 The bandwidth of a heartbeat signal is between 0.5 and 4 Hz (30 to 240 BPM), other frequencies thus need to be filtered.

4.1.2 A reflection PPG measurement device needs to provide the heartbeat signal.

4.1.3 The sensor needs to be worn during exercise, which means that the system needs to be non-invasive.

4.1.4 Because the headset will be worn during physical exercises, motion occurs. The influence of this motion on the heartbeat signal needs to reduced.

a motion filter needs to be designed in order to remove signal components that corrupt the heartbeat signal.

4.2. EFFECT OF LIGHT WAVELENGTH

Before selecting a single or multiple PPG sensor(s) one should look at the effect of the wavelength of light. Different colors of light react differently on human tissue and "[i]t is known that light of short wavelengths (blue and green) penetrates less than light of longer wavelengths (infrared). Therefore, PPG using shorter wavelength optical signals is less influenced by the deeper tissue movements" [14]. Thus two types of light will thus be investigated: green (570nm) light and infrared (950nm) light.
In this thesis the effect of these two light sources will not be elaborately discussed, but the results of both sensors will be compared and a small conclusion will be drawn regarding the different wavelengths.

4.3. CIRCUIT DESIGN

4.3.1. SENSOR

The first step of the design is to select electronic components for the reflective sensor. In order to measure PPG signals the sensor should consist of a light emitter and a light detector. Since it was decided to investigate two different sensors, each with a different wavelength, two pairs of emitters and detectors are needed. Reflective sensors are available with both the emitter and a photo transistor in one package. Using a single package for each wavelength would be the best way to go as the emitter and transistor are already tuned to work with each other. Unfortunately, the 570nm wavelength (green light) package was not available. However, the 950nm wavelength (IR light) package was. The package chosen is the TCRT1000 [27] which has an emitter that uses infrared light with a wavelength of 950 nm. Since no 570nm package was available the sensor that uses green light has to be made out of separate components. A green LED and a Vishay NPN 570nm wavelength photo transistor [28] were used to create our own sensor. Schematic circuits for both sensors can be found in Figure 4.1.

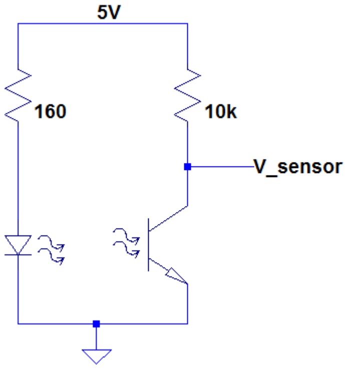


Figure 4.1: SPICE schematic of the IR and green light PPG sensor.

4.3.2. BASIC SENSOR MEASUREMENTS

Test results of this circuit are shown in Appendix A. The measurements were done on the index finger. In Figure B.1 the measurements with the green light sensor are presented. It shows that the heart rate could not be detected, but changes in light intensity did cause changes in the signal as is shown in Figure B.2. The heart rate can not be detected because the contribution of noise on the signal is bigger than the contribution of the heartbeat. The sensor also has issues with the changes in ambient light.

In the measurement for infrared light however, a heart rate can be accurately identified as can be seen in Figure B.3. The difference lies in the fact that the emitter/photo transistor of the green light sensor was made out of individual components and did not consist of a single package. This made it very hard to position the sensor properly on the index finger and made it sensitive to external light sources, such as ambient light. This made that the green light sensor was incapable of detecting the small changes in light intensity caused by the heart rate.

Both signals had a DC offset and some noise. The noise, visible in the pictures at Appendix B, is mainly caused by the oscilloscope and probes rather than by the sensors or power supply, as this noise was also present when a short circuit at the probe was created. The offset and noise can be filtered from the signal using a bandpass filter that will be covered in section 4.3.3. Proper results were obtained using the TCRT1000 and since there was no green light sensor package available it was decided to continue working with the IR sensor package and stop using the green light sensor that was created. Even though it should be possible to get results with green light, the aim was to focus on the motion artifacts which will be discussed later on. Measurements with the infrared sensor revealed that it was insensitive to ambient light. The amplitude of the unamplified infrared sensor signal can be seen in Figure B.3 in the Appendix B. The amplitude is approximately 10 mV. This is a relatively small amplitude and needs to be amplified, this will be covered in section 4.3.3.

4.3.3. FILTER AND AMPLIFICATION

The unamplified signal of the heart rate is in the order of 10 mV and the minimum resolution of the Arduino is 5 mV, which means that the heart rate signal needs to be amplified. The used amplifier is a LM358 dual operational amplifier [29]. For the amplification in a non-inverting amplifier the following equation holds:

$$\frac{V_{out}}{V_{in}} = \frac{R_4}{R_3} + 1 \tag{4.1}$$

In order to get a high resolution measurement with the Arduino Uno, the 10mV signal, as mentioned in section 4.3.2, it needs to be amplified with an amplification factor of around 100. This amplification is created using $R_4 = 100k\Omega$ and $R_3 = 1k\Omega$ resistors resulting in a amplification factor of 101.

In order to properly amplify the PPG signal it needs to be filtered. Since the heart rate will most likely be between 30 and 240 BPM (or 0.5 and 4 Hz) all other signals should be removed. The component values for the filters are determined using equation 4.2.

$$f_s = \frac{1}{2 * \pi * R * C} \tag{4.2}$$

For the high-pass filter a $40\mu F$ capacitor and two $10k\Omega$ resistors in parallel are used to create a resistance of $5k\Omega$. The low-pass filter consists of a $200k\Omega$ resistor and two capacitors of $100nF$ in parallel.

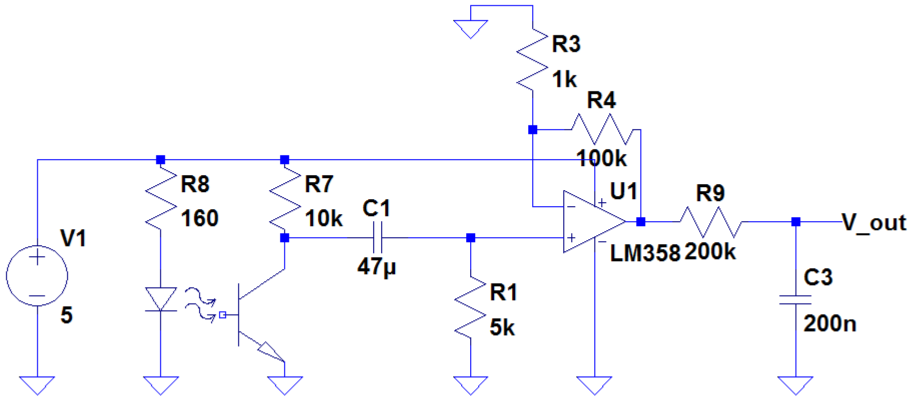


Figure 4.2: SPICE schematic of the sensor, including the high- and low pass filter and amplifier.

4.3.4. SIMULATION

For simulation purposes the sensor circuit from figure 4.1 has been replaced with an voltage supply that generates a $10mV$, $1Hz$ signal with a $100mV$ offset. These values are consistent with the signal from the IR sensor. One can find the outcome of this simulation in Figure 4.3. As told before the minimal resolution of an Arduino is 5mV. If one looks at the simulation it is clear that the peak to peak value is more than enough (1V) to generate a proper resolution on the Arduino.

4.3.5. VOLTAGE OFFSET

In practice this system worked, however, under certain circumstances the voltage at the (+) entrance of the op-amp reached negative values because of the filtering capacitor. In the current design this was problematic at two points in the system: at the op-amp and at the Arduino Uno. Since it is not possible to supply the op-amp with a negative voltage using the Arduino Uno, the op-amp cannot amplify the negative voltages at its entrance and will thus result in a clipping effect at ground level whenever the voltage drops below $0V$. Even if it had been possible to supply the op-amp with a double power supply,

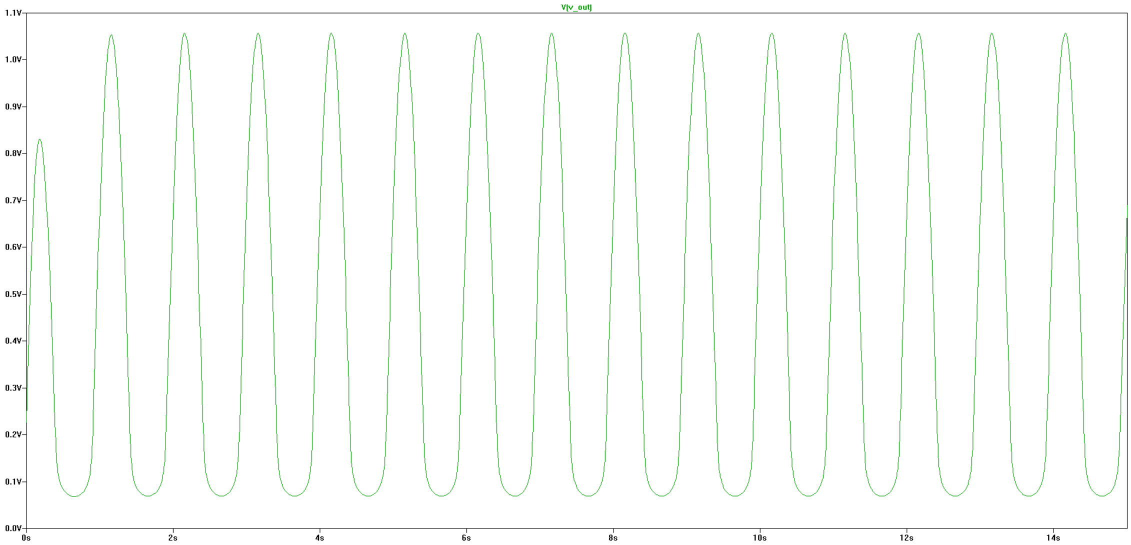


Figure 4.3: SPICE simulation showing the output voltage from the schematic in Figure 4.2.

the Arduino Uno would still have been unable to read out any negative voltages as the range of its inputs is $0V - 5V$, which means that the information of any signal parts with negative values would get lost.

In order to remove the negative values without losing information, it is necessary to create an offset that is high enough to lift the negative voltages, but low enough to avoid clipping at $5V$ at the amplifier. After several measurements with an oscilloscope it was concluded that the voltage at the entrance of the op-amp never drops below the $-10mV$. In order to have a small margin of error it was decided to create a $15mV$ offset using a $5V$ voltage divider with $300k\Omega$ and $1k\Omega$ resistances. The output then has an offset of approximately 1.5V.

In order to apply this offset to the signal, the op-amp's ability to add signals was used. The resulting circuit is shown in Figure 4.4.

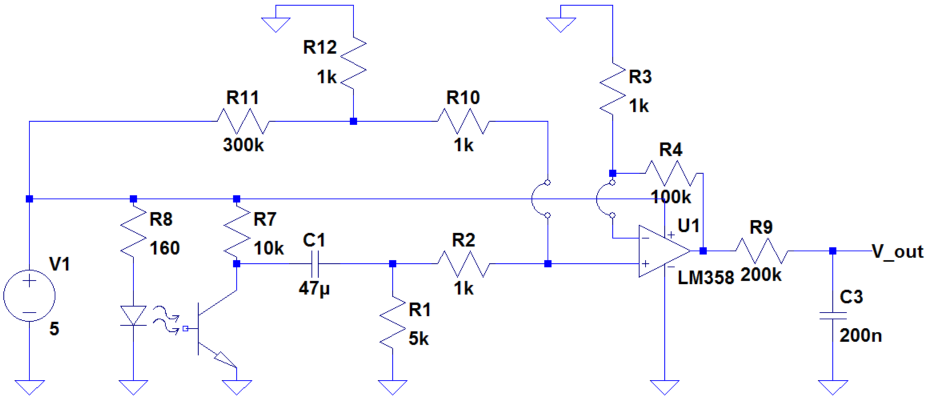
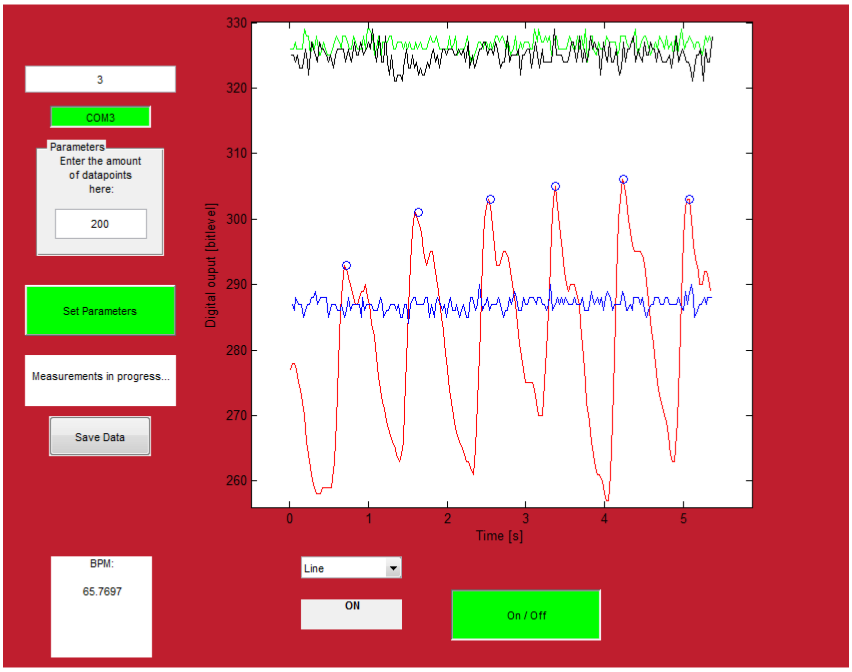


Figure 4.4: SPICE schematic of the sensor including the high- and low pass filter, amplifier, and $15mV$ offset.

4.4. DATA ACQUISITION

The data acquisition is done through an Arduino Uno , a microcontroller board based on the ATMEGA328 [30]. The Arduino Uno has six analog pins, each with a 10 bit resolution with 1024 different integer values. Four of these analog pins are used. The first signal to be acquired will be the heart rate signal. The three other signals are related to motion, which will be discussed in section 5.1. The Arduino Uno is connected to a laptop running MATLAB. For the purpose of data acquisition the GUI, as seen in Figure 4.5, was used. In the GUI the amount of data points can be set on the left side. The data sets can also be saved for later use with the 'save data' button. These data sets are used to test our different concepts in the following sections. Finally, in the bottom left of Figure 4.5, the amount of beats per minute is displayed.



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COM3

Parameters

Enter the amount of datapoints here:

200

Measurements in progress...

BPM:

65.7697

Line

Figure 4.5: GUI for data acquisition.

All measurements in this chapter consist of 200 samples. However, the sample rate is not necessarily the same. The sample rate is limited by MATLAB and changes when the amount of input signals is increased or decreased. Therefore, some measurements showed in this chapter might incorrectly appear to have a higher or lower heart rate.

4.5. RESULTS

The circuit discussed in section 4.3.5 was implemented in order to obtain the measurements. The output, V_{out}, of the circuit is connected to the Arduino Uno, mentioned in section 4.4. Using the data acquisition, also explained in section 4.4, the first measurements are made on a finger without moving the sensor to ensure no motion artifacts are present.

The resulting signal can be found in Figure 4.6. It shows the heart rate in detail and the dicrotic notch, the small valley directly after the main peak, is clearly visible as well.

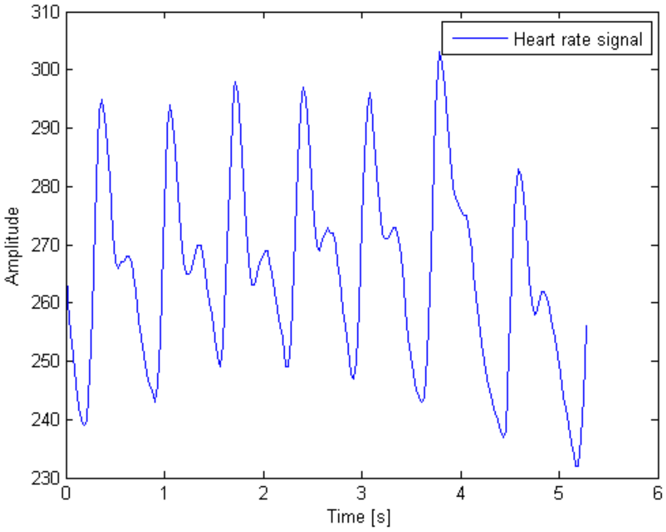

Figure 4.6: Heart beat signal measurement in stationary position (minimal motion)

4.5.1. DIFFERENT MEASUREMENT LOCATIONS

As a next step measurements are done on three different locations around/in the ear: in the ear, on the earlobe, and on the mastoid area behind the ear. One of the requirements of these measurements is that the sensor needs to have proper contact with the skin. Since the accelerometer including (bulky) the IC adapter (this will be further discussed in chapter 5) is already attached to the PPG sensor, it is hard to make proper contact on uneven surfaces. This leads to some results that were not useful, but these results were left out as they do not represent the function of the sensor.

The results of the measurement on the ear lobe can be found in Figure 4.7, the result of the measurement on the mastoid area can be found in Figure 4.8, and the in-ear measurement can be found in Figure 4.9. In all cases the heart beats are clearly visible.

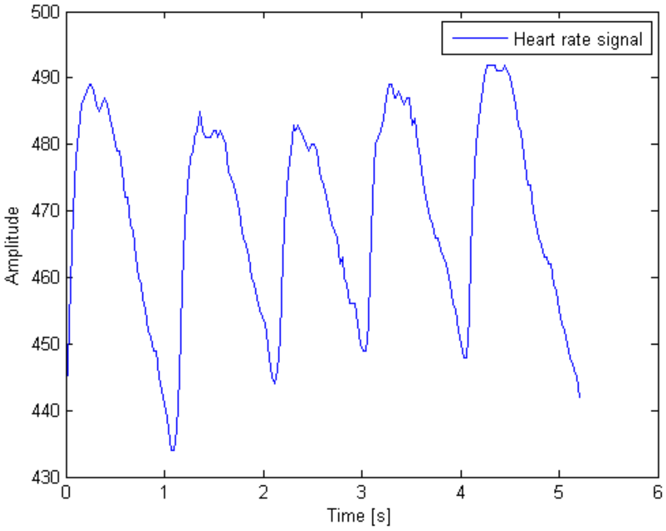

Figure 4.7: Heart beat signal measurement in stationary position on the earlobe.

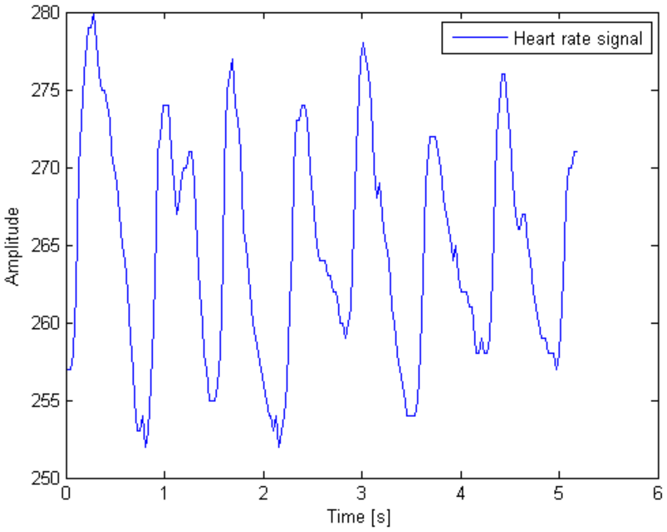

Figure 4.8: Heart beat signal measurement in stationary position on the mastoid area.

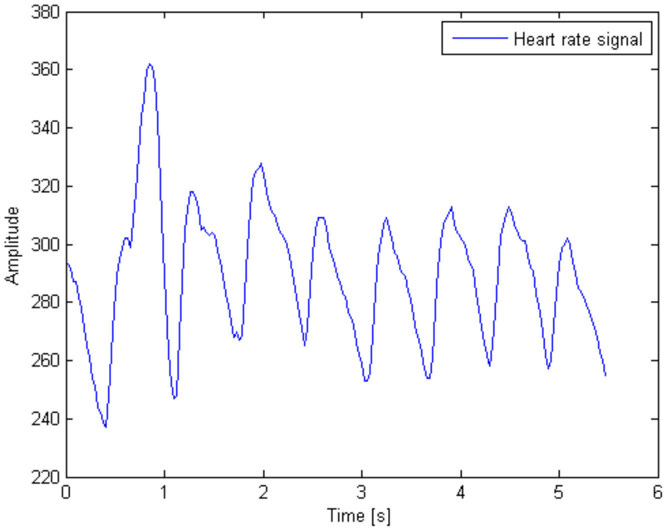

Figure 4.9: Heart beat signal measurement in stationary position in the ear.

4.5.2. POWER USAGE

As ultimately this sensor needs to be implemented in a wireless headset, the power usage is interesting in order to determine how long it can be used before the battery is drained. The current drain of the sensor and amplification/filter circuit is $23mA$, at a supply voltage of $5V$. This means that the circuit uses $115mW$, which is too much for a system that needs to be implemented in a wireless headset. The power usage of the accelerometer was left out, meaning that the total power usage is slightly higher. Reducing the power consumption, however, is not within the scope of this research and will therefore not be further addressed in this paper.

4.6. HEART RATE CALCULATION

The next step is to use basic signal processing to determine the amount of beats per minute (BPM). This can be done with a fast Fourier transform (FFT). From the FFT the frequency of the heartbeat can be determined by finding the highest peak. Having found this frequency, the BPM can be determined with equation 4.3.

$$BPM = 60 * f \tag{4.3}$$

In Appendix D.1 one can find the MATLAB code for these calculations. The code might return a vector with multiple values for the heart rate due to periodic motion artifacts, this will be further explained (and solved) in chapter 5 and 6.

5

MOTION ARTIFACTS

In the aforementioned results for on-ear measurements, the signal can be affected by motion artifacts. Motion artifacts by sports like jogging are in the same frequency bandwidth as the heart rate, typically in the 0.5-2Hz range, which makes proper heart rate detection very difficult.
As a first step the effects of motion artifacts on the heart beat signal is investigated. Typical filter techniques are not applicable and invasive techniques to stabilize the sensor are not desired. This means it is necessary to develop a special way to filter motion artifacts.

5.1. EFFECTS OF MOTION

In order to investigate the effect of motion on the heart rate signal, the motion will be measured using a LIS332AR accelerometer[31]. The accelerometer was fitted on an IC-adapter for easier use. This accelerometer produces a three channel analog signal that is dependent on both direction and g-forces. The three analog signals all represent a single direction, namely the X, Y, and Z direction (see Figure 5.1). Since the chip measures g-forces and not directly acceleration, the DC values of the signals is dependent on the orientation of the chip, as the gravity creates a 1g signal and the chip will not be in free fall. We ignore this DC value in MATLAB by calculating the mean of the 200 samples and subtracting it from all samples subsequently. In Appendix C one can find an overview of the complete system, including the accelerometer.

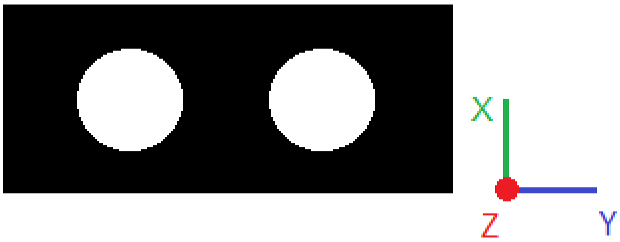

Figure 5.1: PPG sensor with defined motion axis.

The first step is to investigate the effect of each axis of motion on the heart beat signal. It is important to note, that the measurements of motion needs to be done on the same location as where the heart rate is measured. When measuring the heart rate on the head, the motion occurring on the hand for example, is different and not representative. Heart rate signals will be measured together with the motion in the X, Y, and Z direction.
The effect of motion in the X-axis direction can be found in Figure 5.2. Here motion in the x-direction causes a distortion in the signal, a part of the heartbeat signal is flattened due to the induced motion.

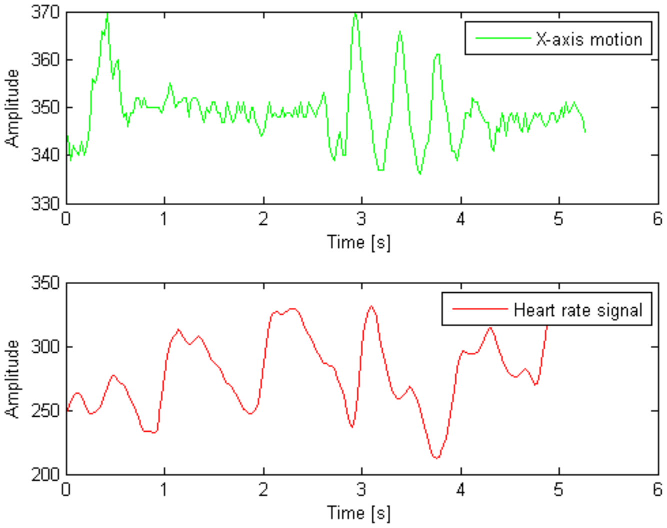

Figure 5.2: Heart beat signal measurement with motion in the X direction.

The effect of motion in the Y-axis direction can be seen in Figure 5.3. It can be seen that the motion flattens the peaks of the heartbeat signal, even though the effect is less than that of motion in the x-axis.

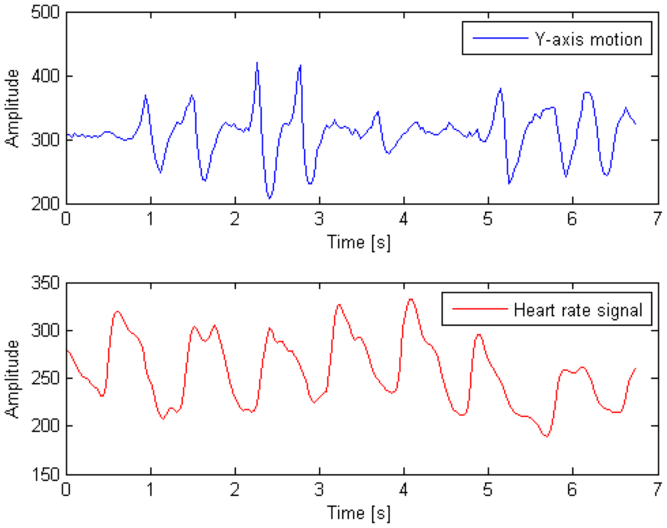

Figure 5.3: Heart beat signal measurement with motion in the Y direction.

Finally the effect of motion on the Z-axis direction can be found in Figure 5.4. Here the effect of motion can be observed as well. The hearbeat signal under the influence of this direction of motion can cause flattened peaks and amplified valleys.

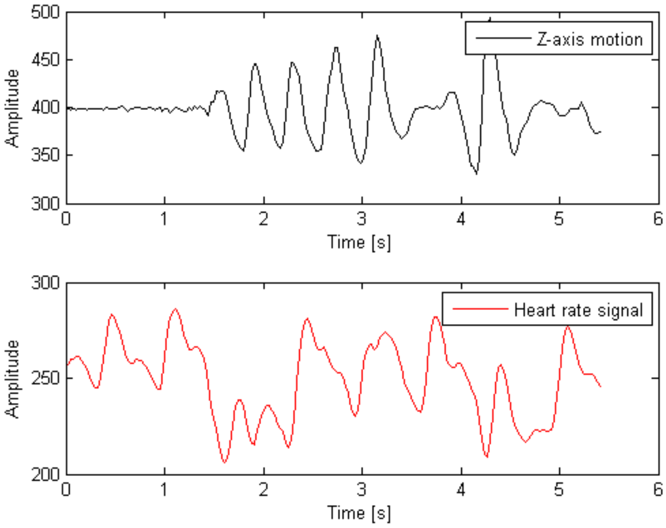

Figure 5.4: Heart beat signal measurement with motion in the Z direction.

5.2. MOTION EFFECT ON BPM CALCULATION

As mentioned in section 4.6, the calculation of the BPM is based on finding the highest peak in the FFT. However, motion may induce unwanted artifacts in the heart beat signal. For the three measurements from section 5.1, the FFT is calculated and it will be investigated whether or not it is possible to receive accurate results for the heart rate, using the current calculation method. In order to determine all possible heart rate values, MATLAB's peak detection is used to identify every peak that is higher than a threshold value. After several tries it was concluded that 0.7 times the value of the highest peak was the the most appropriate threshold value. First the steady measurement without motion is investigated, as can be seen in Figure 4.6. For an adult, a heart rate between 60 and 100 BPM is expected [24]. The FFT of the stationary measurement can be found in Figure 5.5, resulting in a calculated heart rate of 84.5. This is in the range of the heart rate for an adult in a rested state.

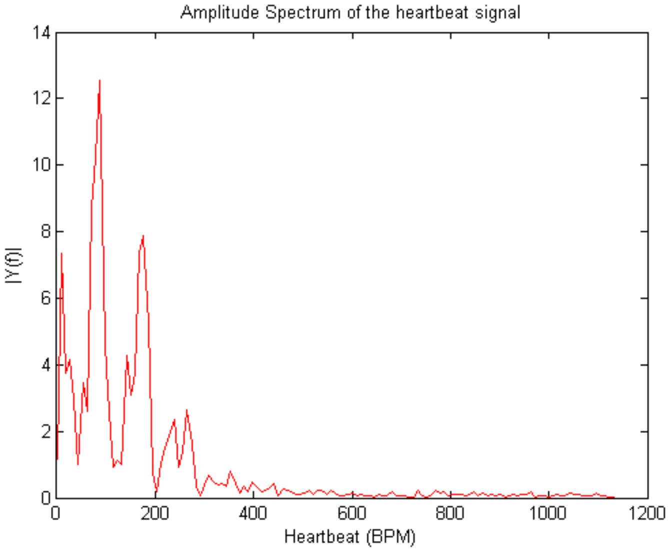

Figure 5.5: FFT of heart beat signal with no motion

The FFT of the heartbeat signal with motion in the X direction, which is shown in Figure 5.2, can be found in Figure 5.6. One tall peak (within the 60-100BPM range) can be identified and corresponds with the heart rate and the result of the BPM calculation is 63.7 BPM.

The FFT of the heartbeat signal with motion in the Y direction, which is shown in Figure 5.3, can be found in Figure 5.7. In this signal only one tall peak stands out and corresponds with the heartbeat. The result of the BPM calculation with this data is 69.3 BPM. Thus it seems motion in the Y direction does not provide problems with the calculation with this dataset.

The FFT of the heartbeat signal with motion in the Z direction, which is shown in Figure 5.4, can be found in Figure 5.8. Here multiple peaks can be identified. The BPM calculation gives us three peaks values. In this case the simple peak detection algorithm can not distinguish the actual heart rate, and returns all these three peak values. As mentioned before, the heart rate of a person that is not heavily exercising should be between 60 and 100 BPM. This means the second peak is expected to be the heart rate, corresponding to the calculated value of 91.6 BPM.

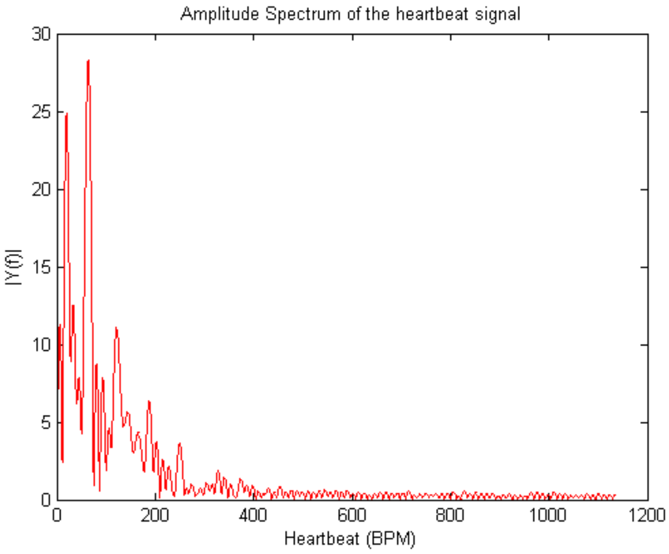

Figure 5.6: FFT of heart beat signal with motion in the X direction.

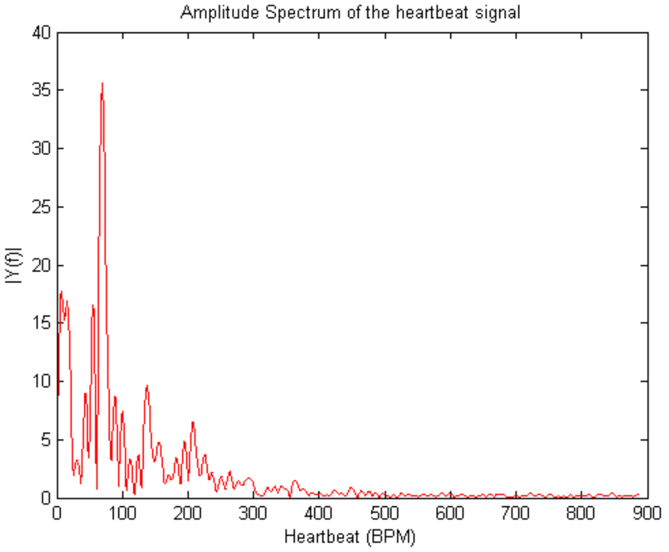

Figure 5.7: FFT of heart beat signal measurement with motion in the Y direction.

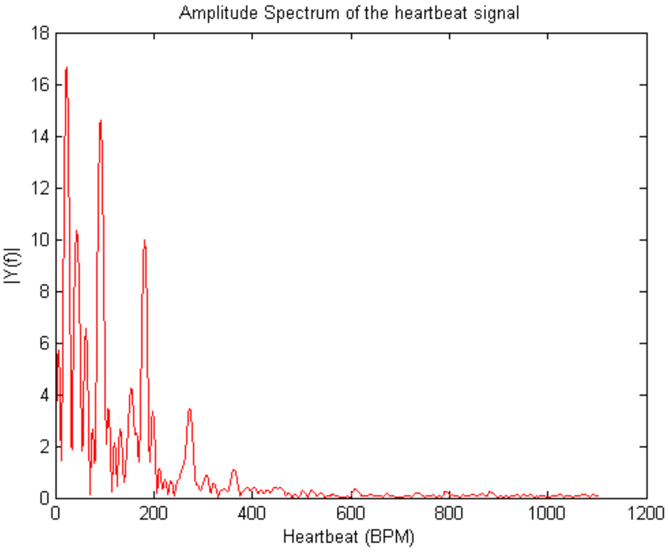

Figure 5.8: FFT of heart beat signal measurement with motion in the Z direction.

6

FILTERS

In order to filter the heart beat signal to minimize the effect of motion on the calculation of the heart rate, certain limits need to be determined and the effect of periodic signals, introduced by this motion, needs to be removed. A part of the MATLAB code of the filter can be found at Appendix D.2. Some parts of the code are left out to give a better overview.

6.1. UPSAMPLING

The resolution of the FFT from the original signal can be calculated with equation 6.1.

$$resolution = \frac{f_s}{N} \tag{6.1}$$

Here f_s is the sample frequency and N is the amount of samples. The resolution of a signal length of 200 samples was too low (around 11 BPM) and due to the varying sample frequency this resolution also varies. To obtain a higher resolution the signals need to be zeropadded.

The amount of zeroes to be added can then be calculated with equation 6.2. Where L is the amount of samples of the signal and the desired resolution is 1 BPM.

$$Zeroes = \frac{f_s * 60}{Resolution} - L \tag{6.2}$$

6.2. DATA REDUCTION

In the first part of the filter all unrealistic values for the heart rate are removed by setting limits. Since the heart rate for any healthy person ranges between the 45 and 230BPM, all other values could be considered unrealistic.

The rate of change of the heart rate is limited as well. Professional athletes are considered to have the best trained heart and therefore the fastest heart rate recovery. For elite Spanish male athletes the heart rate recovery is 153.9BPM per minute [32]. This is equal to 2.66 BPM per second.

Therefore one could consider that heart rate changes higher than 2.66 BPM per second, are unrealistic. For this reason all heart rate values that suggest a change in the heart rate higher than 153.9BPM per minute, are removed from the vector.

This part of the filter is shown in lines 17 to 24, and 38 to 48 of the MATLAB code in Appendix D.2.

6.3. SUPPRESSION OF MOTION BY FREQUENCY ANALYSIS

The second part of the filter (lines 2 to 10, and 26 to 33) removes all values for the heart rate that are introduced by motion. In the code in Appendix D.2 only the motion filter for the Y direction is shown. The filters for the X and Z direction are the same, but are left out in this thesis to keep the code readable. The filter that is implemented compares the frequency spectra of the signals.
First the peaks of the FFT of the motion signal are determined on the same manner as with the heart beat signal. Secondly all values for the motion are compared with the values in the vector of the heart rates. Whenever one of the BPM values of the motion signal matches a value in the heart rate vector (with a margin of error of 2%), this cell in the heart rate vector is set to zero and later on removed (lines 53 to 65).

6.4. DATA HOLDING

It is possible that no heart rate is measured during one cycle, or that the heart rate that was measured was filtered out by one of the filters. For these cases the last measured value for the heart rate needs to be displayed. For this reason the last part of the filter saves the current value for the heart rate for later use. The last measured heart rate then has an uncertainty (u) of

$$u = \frac{159.3}{60} * T \tag{6.3}$$

Where T is the timewindow of the dataset.

6.5. RESULTS

In chapter 4 results of the sensor with and without motion were discussed. Although it was possible to determine a heart rate from the signal without motion, with motion multiple possible heart rates were detected. With the filter described in this thesis it is possible to filter out all motions with a frequency component. In Figure E.1 the result of the heart rate calculation of a PPG signal with motion artifacts is shown in the GUI. These motion artifacts were a result of a jogging motion during the measurement. Figure 6.1 shows that the PPG signal had two big frequency components: one at 88 BPM and one at 120 BPM. As the FFT of the motion signal shows, the 120 BPM component is a motion artifact and not the actual heart rate. Even though the FFT shows two possible heart rates, the GUI in Figure E.1 only displays one heart rate (88 BPM) and filtered out the 120 BPM motion artifact.

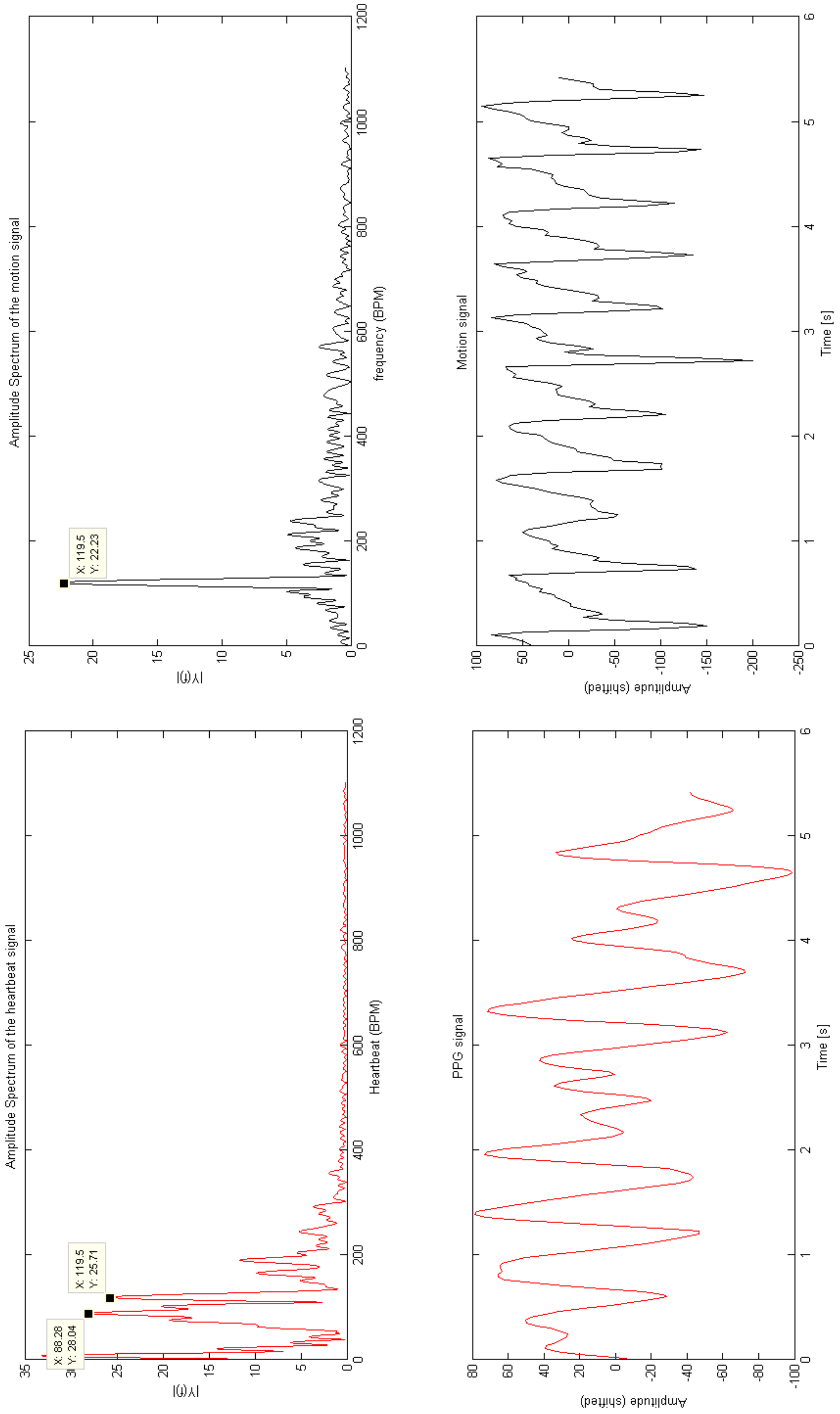

Figure 6.1: MATLAB plots of the measurement from figure E.1. The motion at 119.5 BPM is visible in the heart rate signal, but is removed by the filter before displaying the heart rate at the GUI.

6.6. ADAPTIVE FILTER CONCEPT

In section 6.4, only data that fits certain criteria for the calculation is used. This criteria leads to a large amount of data loss. As mentioned in the introduction, the purpose of this research is mainly focused on heart rate measurements in sports products. The potential risk of reusing one or two data sets due to a too heavily deformed signal is therefore not an issue. However for medical purposes, this data loss is a problem, as precision is one of the main requirements for such applications.

Another issue is that the actual heart beat signal is not reconstructed with the current algorithm. However, the shape of the signal is important for certain medical purposes. In this chapter an idea is given on how to solve the motion artifact problem without data loss and how to reconstruct the actual heartbeat from a deformed heart beat signal.

As mentioned in chapter 3, adaptive noise cancellation can be applied to remove the motion noise. Adaptive noise cancelling (ANC) is a tool to suppress narrowband interference in a signal. The model for the adaptive filter can be found in Figure 6.2. The model is representative for different types of adaptive filters, the only difference being the algorithm used.

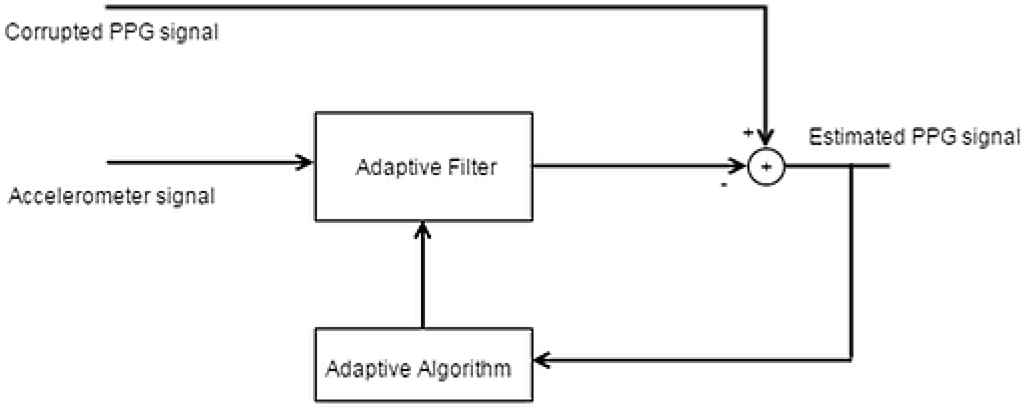

Figure 6.2: Adaptive filter model

The primary input of an adaptive filter consists of the desired signal sequence $h(t)$ corrupted with additive noise caused by motion, $\hat{a}(t)$. The corrupted signal input can also be written as $hc(t) = h(t) + \hat{a}(t)$. In chapter 5 the motion was measured using an accelerometer. The motion can be used as an input for the adaptive filter, $a(t)$. The output of the adaptive filter is an estimation of the desired signal sequence, the uncorrupted heart rate.
In this section only two basic adaptive algorithms are introduced:

- The Least mean square algorithm (LMS).
- The Recursive least square algorithm (RLS).

A LMS filter minimizes the least mean square of the error signal. The error signal is the difference between the desired signal and the actual signal. The LMS algorithm has two important parameters. The first parameter is the length of the filter. This is the number of coefficients. The second parameter is the step size. If the step size is too large, the filter can become unstable and will not result in the correct coefficients.

The major advantage of the LMS algorithm lies in its computational simplicity. However, this simplicity causes for a slow convergence. Recursive least squares is superior in that aspect [33]. The RLS algorithm generally has two important parameters. The first parameter is the order or length of the filter. The second one is the forgetting factor of the filter.

The implementation of these filters are not within the scope of this research, as the research on adaptive filters is a very large topic itself.

7

CONCLUSION

The research done in this thesis provides an alternative way for tackling the motion artifact dilemma. Our work presents a solution to the motion artifacts with the use of the fast Fourier transform and is able to remove periodic influence of motion on a PPG signal.

The goal of this study was to create a heart rate sensor that keeps working during physical exercises and gives a reliable insight on the heart function. At the start of this project some research on motion artifacts on PPG measurements was already done by other researchers, but they all relied on invasive sensors or advanced time consuming filter algorithms [6] [5].

The designed PPG sensor system used a simple filter and amplification. This circuit was successfully simulated and tested, as mentioned in chapter 4. These tests showed motion artifacts and their effects can be seen in chapter 5. An important goal of this thesis was to investigate motion artifacts and to find a solution to this problem plaguing the PPG technology. In this thesis a solution is presented in the form of a motion artifact filter that is based and the use of a accelerometer and frequency analysis, as seen in chapter 6. In this filter the peaks in the FFT of the motion signals and heartbeat signals are compared. During experiments with this configuration, covered in section 6.5, the induced effect of the running motion on the heart rate values was removed successfully.

8

DISCUSSION

While this study was conducted with much care and precision, it is important to emphasize the pros and cons of the choices made. Therefore, this chapter deals with the strengths and limitations of this research.

First of all, the size of the PPG sensor was $7x4x2.5mm$ (L x W x H) [27], which means that this part of the system would not need a size reduction in order to fit into a headset like the BackBeat FIT. The same can be said for the accelerometer, which measures $3x3x1mm$ (L x W x H) [31]. However, the amplification and filter system is currently build using components that would not fit the headset, yet this could easily be remade into a smaller system by Plantronics®. Reducing the size of the system will also help reducing noise influence from the surroundings, as the sensor is currently connected to the filter and amplifier using $30cm$ wires that can act as an antenna, capturing signals generated by other electric devices nearby. By reducing the size of the system and by selecting other components, one can also reduce the power usage. Currently the total power usage (including accelerometer [31]) is $116mW$, which is too high for a wireless headset as it will drain the small battery relatively quickly.

Second, the non-optimal use of the full range of the Arduino Uno is another point of discussion. The current system only uses up to 100 bit levels. The range of 1024 bit levels is therefore not fully used. Changing the amplification of the signal could improve the use of this range.
Exercises that create a motion that lies within the same frequency range as the heart rate, such as running or jogging, were the biggest challenge within this study, as these activities create frequency components that might be displayed as the heart rate. Our MATLAB code removes these frequency components and only displays the actual heart rate as shown in Figure E.1. It is important to note that the deformed heart beat signal is not reconstructed. It was, however, not in the scope of this research to reconstruct the heart beat signal, but only to detect the heart rate.

Third, one of the main problems with the developed filter is that motions with the exact same frequency as the heart rate will result in the deletion of the heart rate value. This means that in the case of a running motion with the exact same frequency as one's heart rate no reliable heart rate can be displayed. Testing this situation is rather problematic, as creating a motion with a frequency identical to the heart rate is very difficult. It is, however, possible that on rare occasions this situation occurs during actual use. Further research needs to be done to improve the filters and to circumvent that these heart rates are deleted.

Fourth, a problem arises when the direction of this research switches to a medical perspective. For medical purposes the loss of data is unacceptable, and therefore advanced filters that use adaptive techniques are preferred. As mentioned at the end of section 6.6, the adaptive filtering techniques are a research topic of itself. There are many different filter algorithms, each of them having its pros and cons. The scope of this thesis was to produce a sensor capable of measuring heart rate through PPG in a wireless headset used by sportsmen. The current algorithm for the data processing fulfills that requirement. The application of adaptive filters would enlarge the scope for medical purposes as well.

Finally, the signal processing done in this thesis was done using MATLAB. For the integration in the wireless headset the signal processing could be done using a smartphone or a digital signal processor.

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A

BackBeat FIT

Figure A.1: The current BackBeat FIT

B

Sensor Measurements

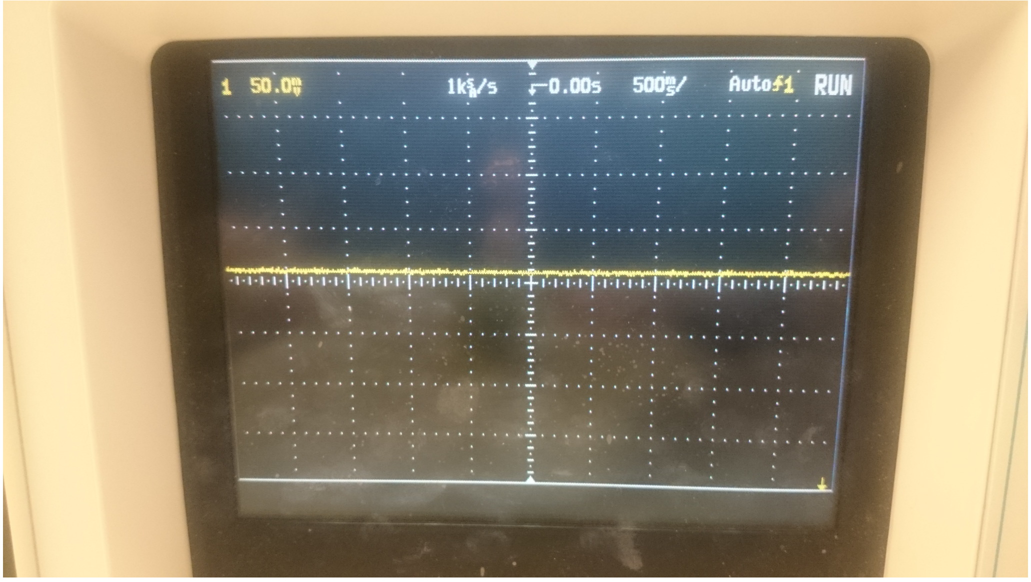


Figure B.1: Scope measurement of green light sensor.

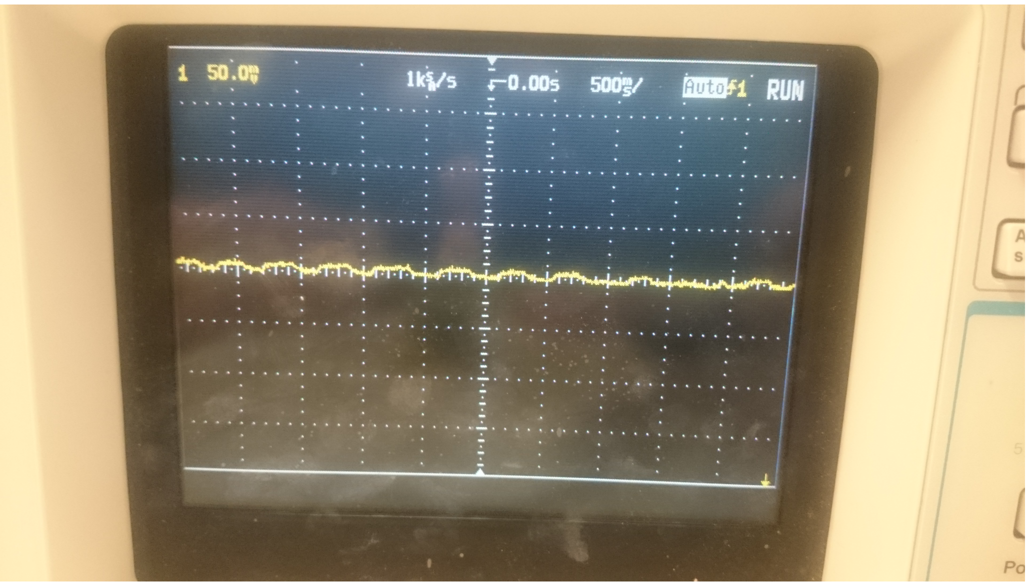


Figure B.2: Scope measurement of green light sensor with changes in light intensity.

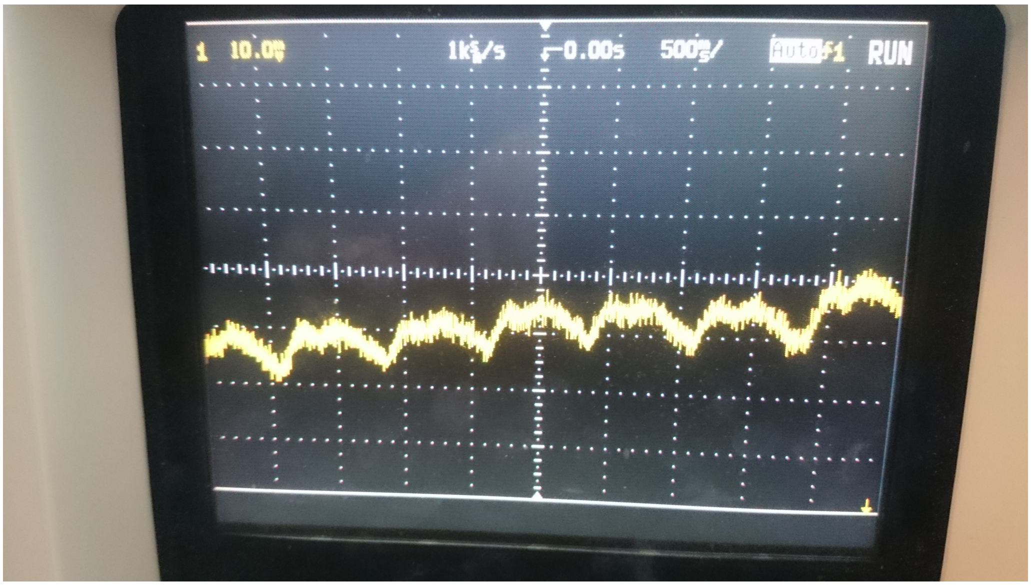


Figure B.3: Scope measurement of infrared light sensor.

C

OVERVIEW OF THE COMPLETE SYSTEM

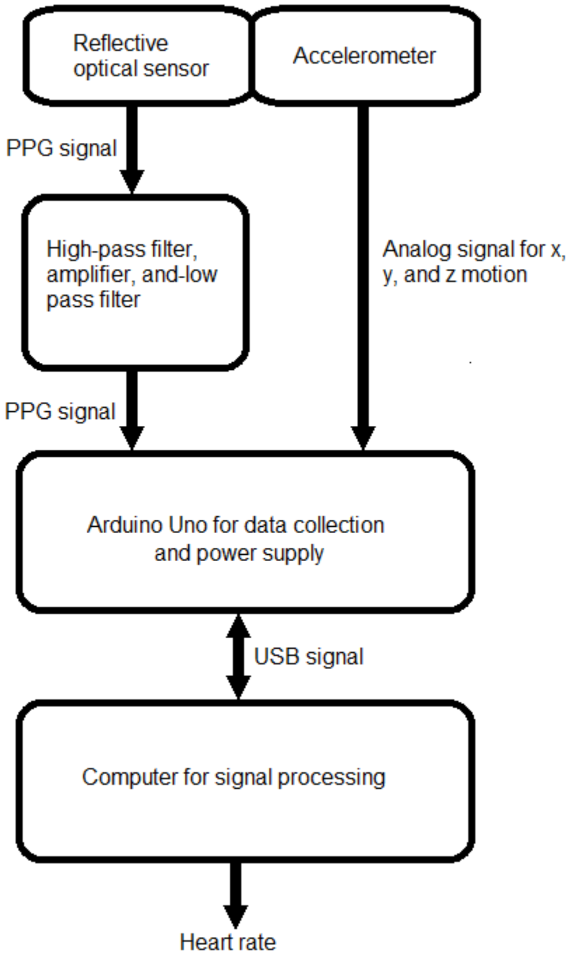


Figure C.1: A schematic giving an overview of the complete system.

D

HEART RATE CALCULATION MATLAB CODE

D.1. HR DETECTION

```
%---------Heart rate calculation---------%
%--Constants--%
Fs = length(HB)/max(time(1,:));
T = 1/Fs;
L = length(HB);
t = T*(0:L-1);
Resolution = 1; %1 bpm res
Addzeros = Fs/((Resolution / 60))-length(HB);

%--Zero padding--%
HB_filt = [HB zeros(1,Addzeros)];
L = length(HB_filt);
NFFT = 2^nextpow2(L);

%--FFT and peaks--%
HB_ft = fft(HB_filt,NFFT)/L;
f = 60*Fs/2*linspace(0,1,NFFT/2+1);
qq = 2*abs(HB_ft(1:NFFT/2+1));
lim = max(2*abs(HB_ft(1:NFFT/2+1)))*0.7
[hight,HR] = findpeaks(qq,'MinPeakHeight',lim);

%--HR--%
HR = (HR-1)*1/(NFFT/2)*(Fs/2)*60;
```

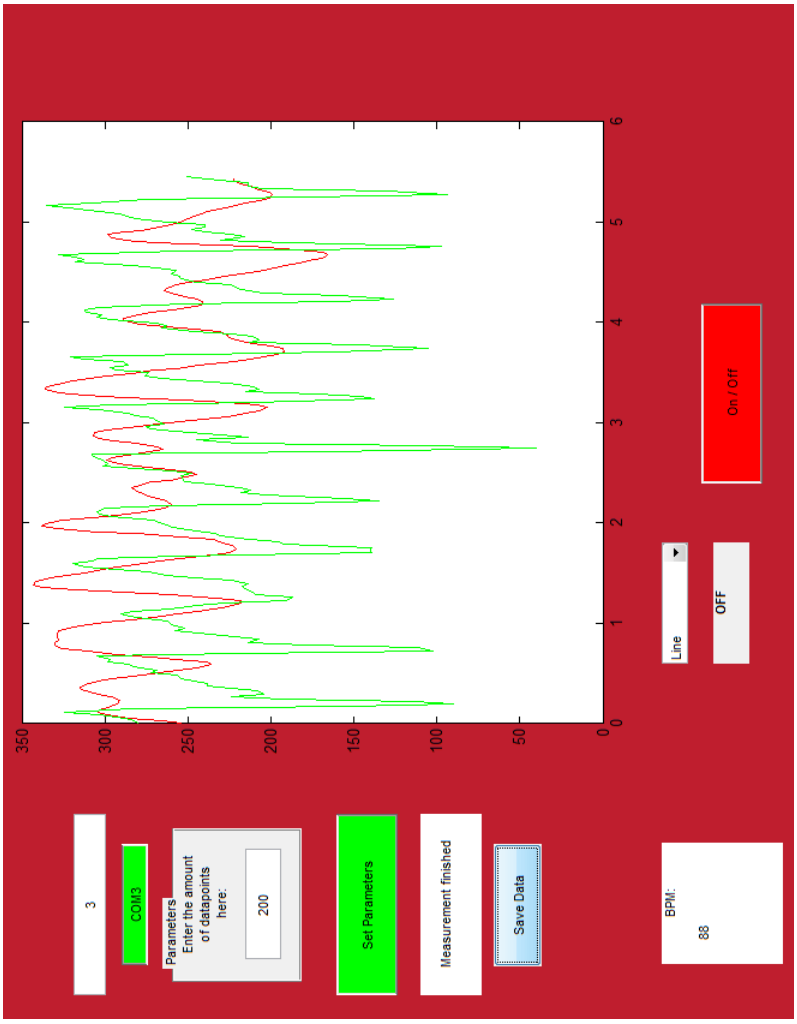
D.2. FILTER INCLUDING MOTION ARTIFACTS

```
%--------Motion artifacts Y--------%
Y_filt = [Y zeros(1,Addzeros)];
Y_ft = fft(Y_filt,NFFT)/L;

fy = 60*Fs/2*linspace(0,1,NFFT/2+1);
qqy = 2*abs(Y_ft(1:NFFT/2+1));
limy = max(2*abs(Y_ft(1:NFFT/2+1)))*0.7;
[Y_hight,Y_motion] = findpeaks(qqy,'MinPeakHeight',limy);

Y_motion = (Y_motion-1)*1/(NFFT/2)*(Fs/2)*60;

%-------Heart beat printing-------%
```

```matlab
L1 = length(HR);
L1y = length(Y_motion);

%------ 50 to 230 BPM bandpass and motion filter, and max 10% deviation from old ...
    HR----%
for i = 1:L1
    if HR(i)<45
        HR(i) = 0;
    elseif HR(i)>230
        HR(i) = 0;
    else
        HR(i) = HR(i);
    end

    for j = 1:L1y
        if (HR(i) > (Y_motion(j)*0.98)) && (HR(i) < (Y_motion(j)*1.02))
            HR(i);
            HR(i)=0;
        else
            HR(i)=HR(i);
        end
    end

    L1_old = length(HR_old);
    HR_old_empty = isempty(HR_old);

    if HR_old_empty == 0
        for j = 1:L1_old
            if (HR(i) < (HR_old(j)-(153.9/max(time(1,:))))) && (HR(i) > ...
                    (HR_old(j)+(153.9/max(time(1,:)))))
                HR(i) = 0;
            else
                HR(i) = HR(i);
            end
        end
    else
        HR(i) = HR(i);
    end
end


%----- Remove all cells of HR with HR = 0 -----%
L1_new = length(HR);

remove_this = [];

for i = 1:L1_new
    if HR(i) == 0
        remove_this(end+1) = i;
    else
        useless = 1;
    end
end

HR(remove_this) = [];

%------use old heart rate when HR is empty------%
Empty_test = isempty(HR);
if Empty_test == 1
    if HR_old_empty == 0
        HR = HR_old;
    else
        HR = 0;
    end
else
    HR = HR;
end
```

E

HEART RATE DETERMINATION WITH MOTION ARTIFACTS FILTER


Enter the amount of datapoints here: 200

BPM: 88

Figure E.1: GUI showing the calculated heart rate from a heart rate signal (red) polluted by motion (green).