Colour based heart rate detection

Heartbeat measurement in wireless music headsets

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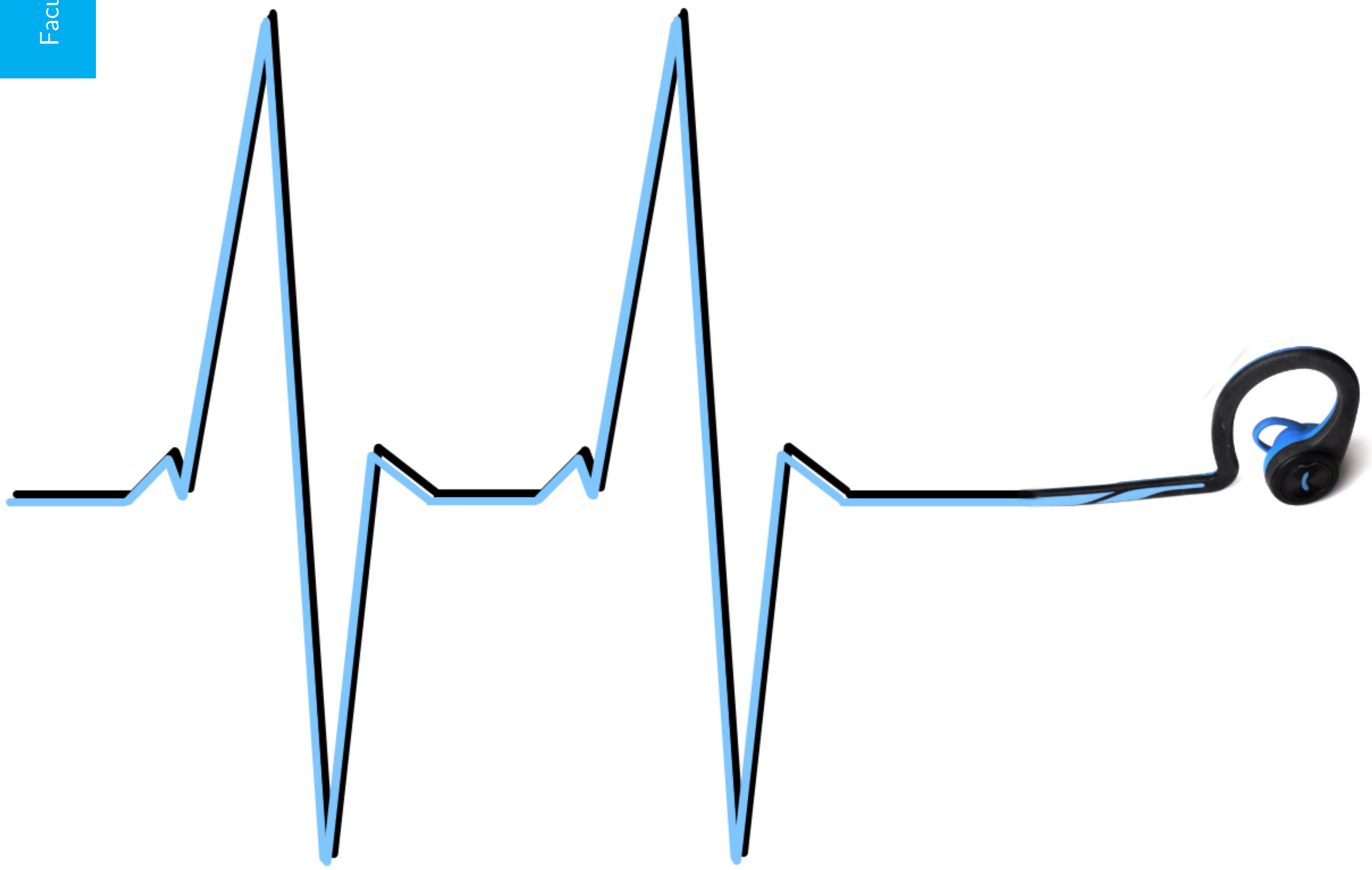
Faculty Electrical Engineering



Delft University of Technology

Challenge the future

Colour based heart rate detection

Heartbeat measurement in wireless music headsets

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.

An electronic version of this thesis is available at
`http://repository.tudelft.nl/`.

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Abstract

In this thesis, assigned by Plantronics®, the analysis and implementation of a colour based heart rate sensor will be discussed, which can be integrated in a sports headset. Two implementations are discussed: an RGB (Red, Green and Blue) sensor and a Light Dependent Resistor (LDR). The former setup identifies colour variations while the latter detects intensity changes in the whole spectrum. The data acquisition is realised by means of an Arduino as Analog-to-Digital Converter (ADC), which sends the information to a computer via a continuous data link. The processing of the received data is then performed in MATLAB.

This document reports the progress and achieved results of the project. At first, the theory behind the measured parameters will be discussed. A concept is designed to proof the principle of measuring colour variations by an RGB sensor and LDR. The next step is constructing a setup that is able to detect skin discolouration, caused by the pulsating blood flow. This periodically changing skin colour can be characterised by amplitude differences. To distinguish the heart rate from noise artefacts, a peak detection algorithm and a Fast Fourier Transformation (FFT) are used. The results of all techniques are subsequently discussed. A conclusion is drawn about these results, after which future recommendations are discussed.

Both the RGB and LDR concept were able to detect colour variations. Although the results of the simulated RGB setup showed promising results, actual skin discolouration measurements did not have consistent results. The LDR configuration did however identify colour intensity changes, resulting in a measurable heartbeat.

Preface

This thesis concludes the Bachelor Graduation Project (Dutch: BAP) as a part of the Electrical Engineering Bachelor at the Delft University of Technology (Dutch: TU Delft). The project is part of the three year curriculum BSC-EE and has to be sucessfully concluded before one can be admitted to a Master. This project started on the 20th of April 2015 and will be concluded on the 3rd of July, just short of eleven weeks in total.

A proposal was done by Dr. Ir. G. de Graaf, in association with Plantronics® and with a team consisting of six members, a possible solution to this proposed problem was explored. The proposal consisted of creating a heart rate sensor that can easily be interfaced with a wireless headset. During this project, a lot of technical experience was gathered, as well as project management skills.

Our thanks goes out to Dr. Ir. Ger de Graaf and Ing. Ron van Puffelen for supervising our plans and progress, providing us with critical hardware and advising us. We further thank Plantronics® for the opportunity to work on this project and providing prototypes. Special thanks goes out to the fellow group members: J. Guyomard, D.C. Kaandorp, A.I. Kanhai and R. Stortelder. They provided help, insight and extra motivation to complete this project.

J.A.G. Jonkman and T.M. de Rijk
Delft, June 2015

Contents

1 INTRODUCTION

In this age of gadgets and smart devices, manufacturers try to add as many features to a device as possible. Well known 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 entirely: sports. With all the new smart devices and their ability to track via GPS, a rise in sporting 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 sport 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 sports and new smart gadgets, Plantronics® opted 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 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:

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

For this thesis, the latter method was thoroughly researched and all results are described in the following chapters. The implementation of this method (skin discolouration) has a common ground with PPG, both use light to measure heart rate. However, the principle behind both methods is very different and not all implementations are similar. Therefore, PPG and skin discolouration were researched separately. More information about the similarities and differences between both methods can be found in Chapter 5.

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Ethical Aspects

The use of a heart rate sensor will be accompanied by two ethical dilemmas, which will be discussed in this chapter.

The main ethical dilemma lays in the interpretation and validity of the data. Plantronics® has a main market of sport enthusiasts that buy their current product: the BackBeat FIT. For these sport applications, any heart rate measurement will do, there are no big consequences to incorrect data. However, if such a product was to be used for medical purposes, an entirely different set of validity rules are to be implemented. The ethical dilemma that rises could be solved by clearly describing the measurement uncertainty and intended use. For example, a disclaimer can be used to inform the customer of the fact that this product should not be used for medical purposes.

Manufactures can integrate the heart rate sensor in their products, for example in a sports headset. This device will keep track of the heart rate of the person running and possibly save this data on another smart device. An ethical problem can occur when this heart rate data is publicly available, or even distributed, for example, to insurance companies. These companies can use this data to detect whether a person has a healthy lifestyle or not. A healthy lifestyle can possibly be derived from the heart rate data: if the person occasionally has a high heart rate (during sport), but for the remainder of the time a normal heart rate, this could imply a healthy lifestyle. When a person constantly has a high heart rate, this can indicate an unhealthy lifestyle. The insurance companies could use this data to estimate the life expectancy of this person and adjust the insurance policy.

3

Design Brief

In order to design a functioning system, certain demands have to be met. As the main purpose of this project was to determine the feasibility of heart rate measurements through discolourations of the skin, the amount of demands is rather small.

The primary demands of this project are:

3.1 examination of the possibility to use a colour sensor to detect colour changes of the skin, caused by heartbeats. A proof of concept must be designed in order to research this possibility.

3.2 The possibility must exist to scale the system to a size that will fit inside the headset.

3.3 The possibility to send the acquired data via a Bluetooth link to a smart device must exist.

In agreement with the client, demand 3.3 does not have to be directly implemented in the sensor system, as this Bluetooth connection is already included in the current BackBeat FIT. Although the list of demands is small, there are preferences which are to be considered. These preferences are not crucial, but they are kept in mind while making design choices.

3.4 The current headset uses a supply voltage of 3 V. A system that uses this supply as well would be preferred, as the need for a different voltage will result in extra conversions.

3.5 The system should use as little energy as possible in order to not diminish the battery life of the headset.

4

Relevant Research

Commercially available heart rate sensors use electrocardiography (ECG) or PPG. PPG has one main disadvantage: current systems are affected when the subject is in motion. Effects and damping of motion artefacts in PPG is being researched by other team members of the research group on the Delft University of Technology [3]. The analysed method consists of a PPG sensor, in combination with an accelerometer to eliminate motion artefacts. Another subgroup of this project is researching temperature based measurements to determine the heart rate [4]. The blood flow causes temperature differences, which can be measured in the ear. Projects of Rice University [5] and Massachusetts Institute of Technology (MIT) [6] have designed systems that measure discolouration of the skin, caused by heartbeats. Visual recordings of the face are used, which consist of multi-pixel measurements and analysis. MIT presented new software that amplifies variations in skin discolouration in successive frames of video, indistinguishable to the naked eye. So, for instance, the software makes it possible to 'see' someone's pulse, as the skin reddens and pales with the flow of blood [7].

The best locations for heartbeat measurements, in proximity to the ear, were also investigated [8], [9], [10]. For the reflection measurements, the most suitable location is behind the ear shell. The light can travel through the skin and blood vessels, and reflect on the mastoid bone. Suitable locations for transmission measurements are on the in- and outside of the ear shell or the earlobe.
Plantronics® has also researched heart rate measuring devices, during a meeting with the systems engineer and senior expert of Plantronics® [11], their progress was discussed and suggestions were made concerning sensor types. ECG was already investigated and concluded to be inadequate for these kind of applications around the ear. The recommendation was made to research temperature and colour based measurements. Analysis and filtering of motion artifacts in PPG measurements were also suggested by Plantronics®.

5

THEORY

This chapter will discuss how to determine the human heartbeat by measuring small colour changes. When blood pumps through the ear periodically, the colour of the ear will also change periodically. In theory, this can be measured by a sensor and used to determine the heart rate. Because the colour variations in the human ear are very small, a simplified model is used to prove the concept. Two types of sensors are used in this project:

- RGB Colour Sensor
- LDR

The prior mentioned pulsating blood flow causes discolouration of the skin, especially in the parts where the veins are superficial. In layman's terms: a body blushes in synchronisation with the heartbeats. As mentioned in Chapter 4, most existing colour based systems use multi-pixel measuring techniques, which are hard to implement in the ear. Therefore, a different concept was designed to better fit the requirements: single pixel measurements. Two methods of single pixel measurements are compared to find the best option: colour differences and intensity changes.
The colour spectrum is often divided into three components: Red(R), Green(G) and Blue(B). A colour is defined by the combination of the different intensities of these spectral components. These intensities can be measured by an RGB colour sensor. An LDR on the other hand, is sensitive to a broad spectrum of light and therefore, the total sum of the R, G and B intensities is measured. These methods are fundamentally different, the former detects three separate dimensions, while the latter measures the sum of these dimensions. The aforementioned methods are compared and the results will be discussed in Section 7.4. Both techniques are measured in two different configurations: reflection and transmission, which will be discussed in the following sections. For both methods it is important that the measurements occur in a dark room in order to minimise interference by ambient light.

As previously mentioned, there is some parallelism between PPG and colour based measurements. For clarification, the differences between both methods will now be discussed. PPG is a type of measurement which measures volumetric changes. This method consists of a light source and a light sensor, frequently a Light Emitting Diode (LED) and a photodiode. The principle behind this measurement is that a larger volume, filled with any type of liquid, will absorb more light than a smaller volume. Therefore, the amount of absorbed light is an indication of the volume. This principle is also used in Atomic Absorption Spectrometry [12]. PPG can be measured in two setups: reflection and transmission. The reflective mode can actually be described as a transmission as well, where light flows through the skin and refracts to the sensor.
Colour based measurements utilise the before mentioned principle that the blood flow pulsates, and therefore skin discolours periodically. This method focuses on colour measurements and measures

light intensities. There are some setups that have a common ground with PPG, however, the measurement principle is fundamentally different. There are many different ways to accomplish colour based measurements, and only some have a slight overlap with PPG.

5.1. REFLECTION MEASUREMENTS

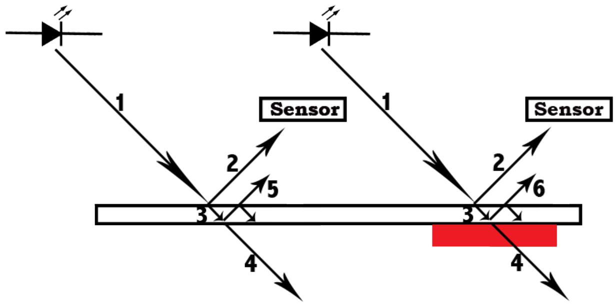
Keeping in mind that the complete heartbeat sensor has to fit within the current BackBeat FIT, reflection measurements are a possible solution because these can be easily implemented in the current design. By placing a sensor and a white or red LED on the inside of the ear, shielded from ambient light, small variations in skin colour may be detected. The light will reflect on the surface of the inner ear and its reflection can be measured by an LDR or an RGB sensor. The intensity of the different colours of this reflected light depends on the surface colour of the inner ear, which is dependent on the blood flow. Two models of this principle are depicted in Figure 5.1. The difference between the two models, facing and non facing, will be discussed in Chapter 6. Some effects, such as refraction, are neglected in this model, as their effect is minimal to these types of measurements. One important effect that cannot be ignored is scattering.

When an irregular surface is illuminated, reflection of light will occur in different random directions. This is called scattering. Scattering can interfere with the reflection measurements. It is important to realise that the main concern about this effect is the difference in scattering in two situations (less or more blood), as this will influence the measurements.

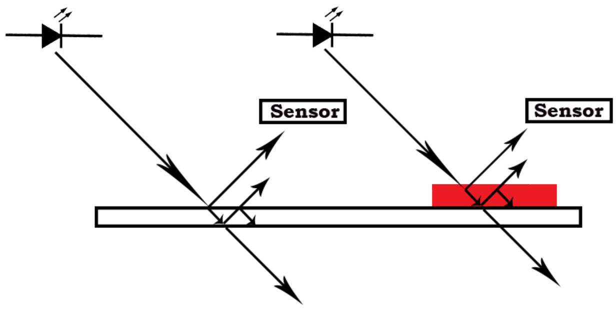
A short summary of the signals in Figure 5.1a:

1. an incoming beam of light.
2. Reflected light from the surface of the medium.
3. The transmitted light from the surface layer.
4. The transmitted light through the medium.
5. The reflected light from the bottom of the medium.
6. The reflected light from the bottom of the medium, altered by the red colour below.

The heart rate can be measured by comparing the intensity and spectral components of the reflected light (beams 5 and 6), which will differ due to the colour difference at the bottomside of the leather.



(a) Not facing the sensor (NFS)



(b) Facing the sensor (FS)

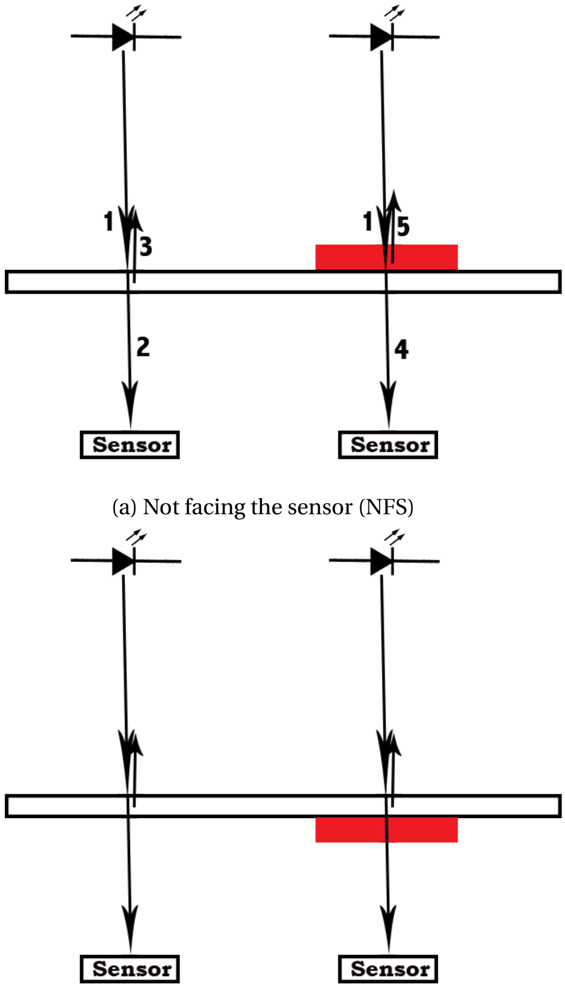
Figure 5.1: Model of reflection measurements

5.2. TRANSMISSION MEASUREMENTS

By placing the sensor on the outside of the ear, for example the ear shell or earlobe, and the LED on the inside, the transmission of light through the ear can be measured. Again, the intensity of the spectral components of this transmitted light depend on the blood flow, so heart rate detection should be possible. In this case, scattering can be neglected, as it will have no effect on the transmitted light. Only the transmitted light through the medium is detected by the sensor. Scattered light reflects and thus will not be detected.
In Figure 5.2, the optical theory behind this type of measurement is illustrated. The difference between both setups will be discussed in Chapter 6. There are five main light beams in this case:

1. the incoming beam, emitted by an LED.
2. The transmitted beam, this beam will be measured by the sensor.
3. The reflected beam, not relevant for this measurement.
4. The transmitted beam in case of discoloured skin, this beam is measured by the sensor and will differ from beam 2.
5. The reflected beam, different in case of discoloured skin.

By comparing beams 2 and 4, the colour of the skin (natural or red) can be deduced.



(a) Not facing the sensor (NFS)

(b) Facing the sensor (FS)

Figure 5.2: Model of transmission measurements

6

DESIGN & IMPLEMENTATION

To prove the concept of measuring colour variations of skin, a simplified model is used. Initially, the system was tested *in vivo* (Latin: within the living), but the results were inconclusive. Therefore, an exaggerated setup was used to determine whether the system is feasible to work. This model consists of a natural piece of leather (Figure 6.1a), a light sensor (RGB or LDR) with a circuit to read the sensor output, and an LED. Depending on the measurement (transmission or reflection) the sensor and LED are either placed next to each other or on different sides of the leather, as demonstrated in Figure 5.1 and Figure 5.2. To simulate a pulsating blood flow, one side of the leather is partly coloured red. This leather is then moved to the left and right, with respect to the sensor and LED. This movement causes the sensor to alternately face the red and the natural part of the leather, which can be interpreted as a pulsating flow. The effect of this movement is depicted in Figure 5.1a up until Figure 5.2b. In every image, the right part consists of the situation where the sensor is above or below the red part, while the left part shows the situation where only the natural coloured leather is visible to the sensor. There are two different approaches to measure the reflection and transmission. The sensor can either directly face the alternating red/natural piece of leather, or face the back of the leather.

FACING THE SENSOR (FS)

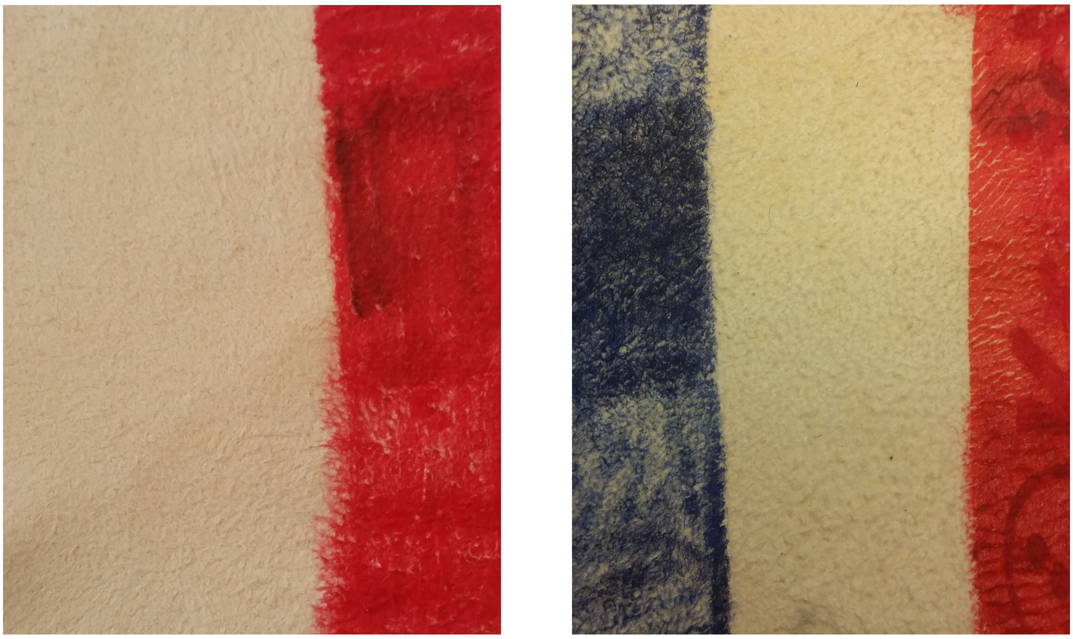
In this implementation, the sensor directly faces the alternating red/natural piece of leather. Because the sensor can now 'see' the changes in the colour directly, a relatively large voltage difference at the output is expected when moving the leather left and right. This method will be indicated by FS. In Figure 5.1b and Figure 5.2b, two setups (reflection and transmission) are displayed in the FS configuration.

NOT FACING THE SENSOR (NFS)

The more realistic approach is when the sensor is placed on the other side of the piece of leather (the side not partly coloured red). Now, the sensor does not 'see' the colour change directly and a lower voltage difference between the red and natural coloured leather is expected. In the following text and figures this method will be referred to as NFS. In Figure 5.1a and Figure 5.2a, the reflection and transmission setups are displayed in the NFS configuration.

DATA ACQUISITION

To capture the output signals, two measurement devices are used: an oscilloscope [13] and an Arduino UNO. The Arduino uses an Atmel ATmega328P [14]. This chip includes a 10-bit ADC, which is used to measure the analog output signal. As this signal has a range of 0 to 5 V, the stepsize is ~5 mV. The Arduino is controlled by Matlab, which enables the function to directly transfer the data to a computer for processing. An open source code [15], in combination with a Graphical User Interface (GUI), was used to establish a continuous connection, control the Arduino and acquire data. The GUI can be seen in Appendix B. The continuous data link lowers the sample frequency to approximately 145 Hz (experimentally determined), which is high enough for this application. Caution has to be taken as



(a) Used in the test setup (b) Used for the spectral component measurement

Figure 6.1: The different pieces of leather

reading multiple inputs will result in a lower sample frequency, i.e., two concurrent channels will each get a sampling frequency of 72.5 Hz. The expected heart rate data will be located in the frequency band of 0.5 - 4 Hz. A maximum of four channels are read concurrently, resulting in approximately 36 Hz which is high enough for the heart rate signal to be detected. In order to compare the measured heart rate to the actual value, a smartphone application is used [16].

LIGHT SOURCES

The chosen LEDs (red and white) have different light intensity (Candela). The intensities of the red and white LEDs are 1.5 and 3.4 cd, respectively. When the LEDs are used for the measurements, the output voltages of the sensors have to be scaled when comparing these, as the intensity is different. The results of the comparison are discussed in Section 7.1. The LED specifications are given below. By using these specifications, the intended light intensity can be reached (1.5 and 3.4 cd). The specifications of the red LED are:

- Forward voltage: 2.1 V
- Forward current: 20 mA
- Dissipated power: 42 mW
- Intensity: 1.5 cd

The specifications of the white LED are:

- Forward voltage: 3.2 V
- Forward current: 20 mA
- Dissipated power: 64 mW
- Intensity: 3.4 cd

In addition to these specifications, the compositions of the spectra also have to be considered. The intensity of the spectral components of the white LED is not evenly distributed in the spectrum. The red LED transmits electromagnetic waves around one specific wavelength and has a very small bandwidth. These spectra can be seen in Figure C.1 in Appendix C. In order to apply the correct voltage and supply enough current, a resistor is placed in series. Its value is determined by Ohm's law:

$$R_{red} = \frac{U_{source} - U_{red}}{I_{red}} = \frac{5 - 2.1}{0.02} = 145\ \Omega \tag{6.1}$$

$$R_{white} = \frac{U_{source} - U_{white}}{I_{white}} = \frac{5 - 3.2}{0.02} = 90\ \Omega \tag{6.2}$$

6.1. RGB-TECHNIQUE

For this technique, a Kingbright RGB Color Sensor [17] is used to detect minor colour changes. This sensor contains three photodiodes, each with a different colour filter. The red and green channel have a similar output current, the blue channel has a much lower output current at the same light intensity. The spectral sensitivity of the RGB sensor is illustrated in Figure C.2 in the appendices. As can be deduced from this figure, the sensor is less sensitive for blue light, which explains the lower current value. In order to compensate for this, the signal can be amplified in Matlab or the circuit amplification can be altered for this specific colour. However, this compensation was not used because the difference in amplitude of the blue channel is the least relevant, and the difference is still clearly visible. As the difference in induced current between red and green is small, this difference is neglected. As the main focus of this project is detecting colour changes due to blood, the red channel is the most important. All three signals combine to a colour spectrum, which can also be used to measure colour differences. In this case, the blue channel has to be amplified in order to compare these spectra.

6.1.1. FIRST CONCEPT

The first circuit concept to measure colour variations using an RGB sensor can be seen in Figure 6.2a. For this circuit, an OP177 op-amp [18] is used because of its high input impedance (200 GΩ) and low bias current (2 nA). An op-amp with a lower input impedance will have a larger bias current, resulting in an undersized output signal.
The typical current values of the RGB sensor are between 22 nA and 498 nA [17]. However, these values are given for specific amounts of light (100 and 1000 lx). While using the previously mentioned LEDs, a much higher light intensity is generated and the induced current is higher. Measurements with a multimeter [19] revealed a maximum current of 8 µA. This current has to be converted to a voltage before it can be read by a oscilloscope or Arduino. This can be done by using a current to voltage amplifier, which can be seen in Figure 6.2a. As previously mentioned, the Arduino can detect a minimal change of ~5 mV and has a maximum input amplitude of 5 V. To make sure the signal variations can be detected by the Arduino, a 560 kΩ resistance is used. The following calculations were done to obtain this resistance:

$$\frac{5\ \text{V}}{8\ \mu\text{A}} = 625\ \text{k}\Omega \tag{6.3}$$

In order to remain safe from clipping and inspired by frequently used circuits, the chosen resistance was lowered to 560 kΩ. The op-amp has to be supplied by a symmetric power source, as the output signal will be negative.

6.1.2. SECOND CONCEPT

To further decrease the bias current, op-amp TLC271 [20] is used because of its high input impedance. This op-amp has the following specifications:

- Low bias current: 60 pA
- High input impedance: 1 TΩ

The TLC271 uses an asymmetric power supply (0 - 5 V). The circuit, as shown in Figure 6.2a, produces a negative voltage at the output which this op-amp cannot produce. To counteract this effect, the op-amp is biased by connecting a 3.3 V source to the positive input pin, as seen in Figure 6.2b. This voltage was chosen because it was almost halfway the source voltage and easily accessible on the Arduino. The op-amp attempts to create the same voltage (3.3 V) at the negative input pin. To maintain a 5 V voltage across the RGB sensor, an 8.3 V source is connected to the sensor instead of the 5 V source used in the previous concept.

6.1.3. THIRD CONCEPT

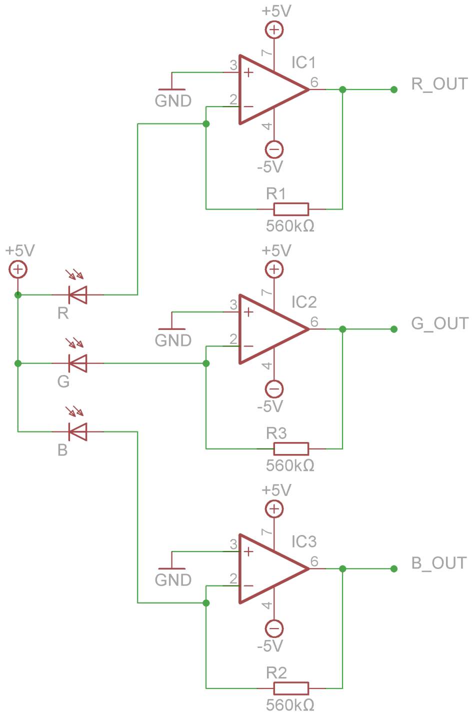
The final concept uses a voltage-to-voltage amplifier to amplify the signal, which can be seen in Figure 6.3. This concept also uses the op-amp TLC271 because of its suitable specifications. Again, a 560 kΩ resistor is used to convert the current to a voltage. This voltage is amplified by a factor two in order to increase the signal's amplitude. The op-amp is also used as a buffer. As the op-amp has a large input impedance, (almost) all the induced current from the photodiodes in the RGB sensor will flow through the resistor. If the op-amp would not be used, a part of this current can leak to the measuring device if its input impedance is low and the accuracy would decrease. To prove the concept, eight situations are tested. These situations can be divided into two groups: FS and NFS. Both groups consist of four setups:

1. Transmission: a red LED [21] is placed on one side of the leather while the sensor is placed on the other side, as illustrated in Figure 5.2. As previously discussed, the leather will be moved, causing the sensor and LED to alternately face the red part of the leather or the natural part. This simulates the blood flow. The sensor will detect the colour change through the leather. This situation is used as a proof of concept to see if this measurement method is viable to work.

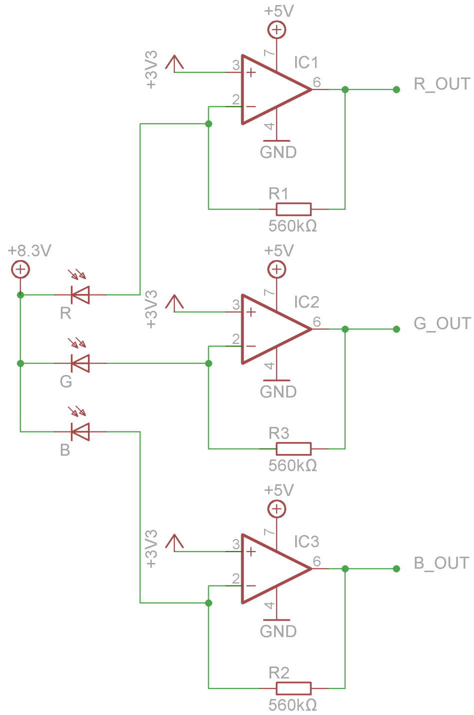
2. Reflection: a red LED is placed next to the sensor, on the same side of the leather. Figure 5.1 contains schematic illustrations of this setup. In contrast to this figure, the sensor and LED will be positioned on the same height and in very close proximity of each other. The piece of leather is shifted left and right, and the sensor and LED will remain still.

3. Transmission: a white LED [22] is placed below the leather. This concept is the same as the earlier transmission measurement, with the difference that a white LED is used. An example of an application of this transmission measurement is when the sensor is placed outside the ear (for example on the earlobe or ear shell) and the LED is placed inside the ear. The sensor will detect the colour changes by the pulsating blood. This concept is tested by keeping the sensor and LED on a fixed position and moving the sheet of leather left and right.

4. Reflection: a white LED is used. The intensity and spectral components of this reflected light will depend on the colour of the leather under the sensor. The changes in the RGB values can be interpreted as a heartbeat.



(a) First concept



(b) Second concept

Figure 6.2: Measurement circuit for the Kingbright RGB Color Sensor

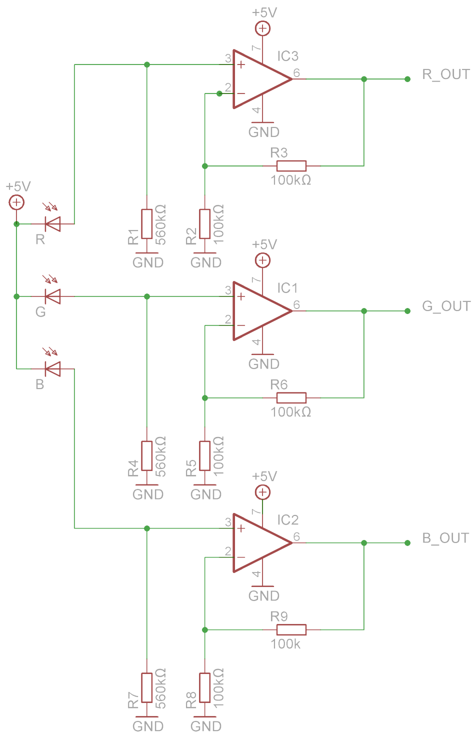


Figure 6.3: Third concept using the Kingbright RGB Color Sensor

6.2. LDR-TECHNIQUE

A Sinolex LDR is used for this implementation [23]. As an LDR is sensitive to a large spectrum instead of a single colour, it is frequently used as an ambient light sensor. The peak response of the LDR is located at 550 nm. Since the inner ear is dark, a light source is necessary to illuminate the ear and this comes to an advantage. The flow of blood results in a red discolouration of the skin. Therefore, if a red LED is chosen, the LDR will only be able to measure the amount of red light, as there is no other source of light. By this logic, a red light sensor is created. While performing the *in vivo* measurements in Section 7.7, it was noticed that by using a white LED, heartbeats could be detected manually. The pulsating discolouration of the skin can be clearly seen. Therefore, a white LED was used as well.

The circuit consists of a voltage divider with the LDR and a resistor, as seen in Figure 6.4. The resistance of the LDR depends on the amount of light, so the voltage across the resistor is also controlled by the light intensity. A 10 kΩ resistor was chosen in accordance with the range of LDR resistance.

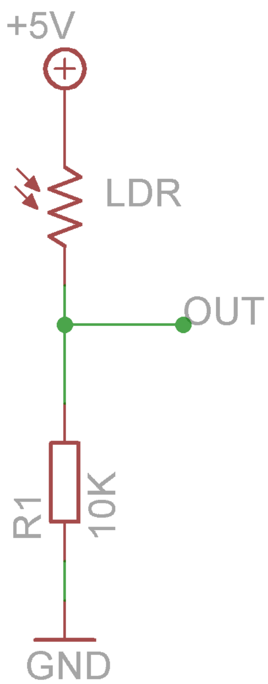


Figure 6.4: Model of the LDR circuit

6.3. MOTION ARTEFACTS

The results of the first measurements (Subsection 7.2.2) looked very promising, but it is not clear at what times the leather was moved. Therefore, some peaks could be caused by motion artefacts instead of actual colour changes.

In order to identify these motion artefacts, a pushbutton was used. While this button is pushed, a new signal is turned high. The chosen convention was to press the button when a steady-state occasion occurs, i.e., when the leather is not moved. Results of this measurement can be seen in Section 7.3.

As formerly discussed, the sampling frequency per channel depends on the amount of channels used. Because this pushbutton will require an extra input, the sampling frequency of the data channels will decrease. Therefore, this pushbutton is only used to identify the motion artefacts once. As seen in the results in Section 7.3, the motion artefacts can clearly be identified as peaks, while the simulated heartbeat resembles a square wave. For these reasons, the pushbutton was not used in further measurements, as motion artefacts can be manually identified.

In the final *in vivo* implementation in the ear, it will not be possible to use this pushbutton to indicate when the body is in motion. However, as seen in Figure 7.5, all channels have similar artefact peaks. The intensity of the blue light could be used to filter the motion artefacts. This concept will be further discussed in Section 7.3.

6.4. PEAK DETECTION AND FILTERS

To detect heartbeats from the measured data, a peak-finder algorithm has been written. This algorithm uses a few parameters which help to find the correct heartbeat-peaks instead of other peaks, originating from noise artefacts. This peak detection algorithm does not filter out all motion artefacts. Very high peaks, caused by motion, will still be detected as a heartbeat. A brief list of parameters and functions are listed below:

- a minimal peak height of $0.7 * (\max(x) - \min(x)) + \min(x)$ is implemented. Peaks lower than this height are probably noise artefacts and should not be detected.
- In order to filter motion artefacts, a minimal peak distance is defined. As a minimal heart rate, 30 beats per minute (BPM) was chosen. Depending on the amount of input signals, the sampling frequency is different, as previously discussed. The minimal peak distance is thus also dependent on the amount of input signals.
- A moving average filter is used to filter very low/high (unrealistic) heartbeat readings.

A second possibility to determine the heartbeat uses FFT. This transformation will calculate all the different frequencies in the data signal. The frequency of the heartbeats should be easily identified in this Fourier spectrum. The advantage of this peak detection is that, if the data signal contains a clearly visible heartbeat, there should be only one extremely high peak: the heartbeat frequency. Noise and motion artefacts have different frequencies, so if only the frequency band of heartbeats (0.5 - 4 Hz) is analysed, artefacts outside this band will be irrelevant. Zero padding was used to create a resolution of 1 BPM ($\frac{1}{60}$ Hz) in the FFT. The resolution of the FFT is described in the following equation:

$$\text{resolution [Hz]} = \frac{F_s}{N} = \frac{1}{T_s} \tag{6.4}$$

In this equation, F_s is the sample frequency [Hz], N is the total amount of samples, and T_s is the sample time [s]. From Equation 6.4, the conclusion can be drawn that a sample time of 60 s is required. The resulting heart rate will then be an average of these 60 s. To solve this problem, zero padding was used. After the actual sample time, the rest of the 60 s was filled with zeros.

The first method of peak detection has to find all the peaks and if the parameters are not entered correctly, a mistake is easily made, resulting in flawed result. Both methods have the need for a longer measurement time in order to determine an accurate heartbeat. This disadvantage rejects real time monitoring, but a delayed, continuous data stream is still optional for both methods.

7
Experimental Results

The measurement results of the concepts and circuits in the previous chapter will be discussed here. For consistency, all the measurements begin with the sensor under or above the red coloured part of the leather, as can be seen in the right part of Figure 5.1 and Figure 5.2.

7.1. LED calibration

As discussed in Subsection 6.1.3, the different light intensities of the red and white LEDs were measured at different distances. These measurements were done in a dark room to minimise ambient light effects. The results are depicted in Appendix D. The red intensity of the white LED will differ from the red LED and this can influence the data as well as the final choice for a white or red LED. Another aspect to consider is the dissipated power of the LEDs. A lower power dissipation is preferred, conform preference 3.5 in Chapter 3. To draw a proper conclusion, this calibration has to be taken into account.

7.2. Concept results

The results of the three RGB concepts and the LDR concept will be discussed here, in combination with the (dis)advantages. Further results will be discussed later on.

7.2.1. First and second RGB concepts

The first setup has several problems. As the output signal of the RGB sensor is very small, the conversion to the desired output voltage without noise is challenging. This problem applies to all concepts using the RGB sensor. Another disadvantage is the negative output voltage, which has to be inverted in order to use the Arduino as measurement device. This problem is easily solved, but costs extra components, and therefore energy. To easily test this implementation, an oscilloscope was used to read the (negative) output signal. During these tests it became clear that large intensity differences can be detected. It was however hard to detect small differences in light intensity, such as differences by the setup described in Chapter 6. The final disadvantage is the synchronous source: from design preference 3.4 in Chapter 3, it is clear that an asynchronous source is preferred, as this source is available on the current product.

Figure 7.1 shows the result of a reflection measurement using a white LED in FS mode. It is clear that the principle works, but the difference in signal amplitude is rather small: about 200 mV.
When performing a transmission measurement, it became clear that the signal was undetectable. This can be seen in Figure 7.2.

The second concept has essentially the same problems as the first concept, except the synchronous source. By biasing the op-amp, the output signal will not become negative and an asymmetrical power supply can be used. As seen in Figure 6.2b, this setup uses a 3.3 V source to bias the op-amp, a 5 V source to power the op-amp, but also an 8.3 V source for the RGB sensor. To provide these sources, a minimum of two DC/DC converters has to be used. The problem mentioned before is still not resolved by this implementation: it is still hard to detect small colour differences in light intensity.

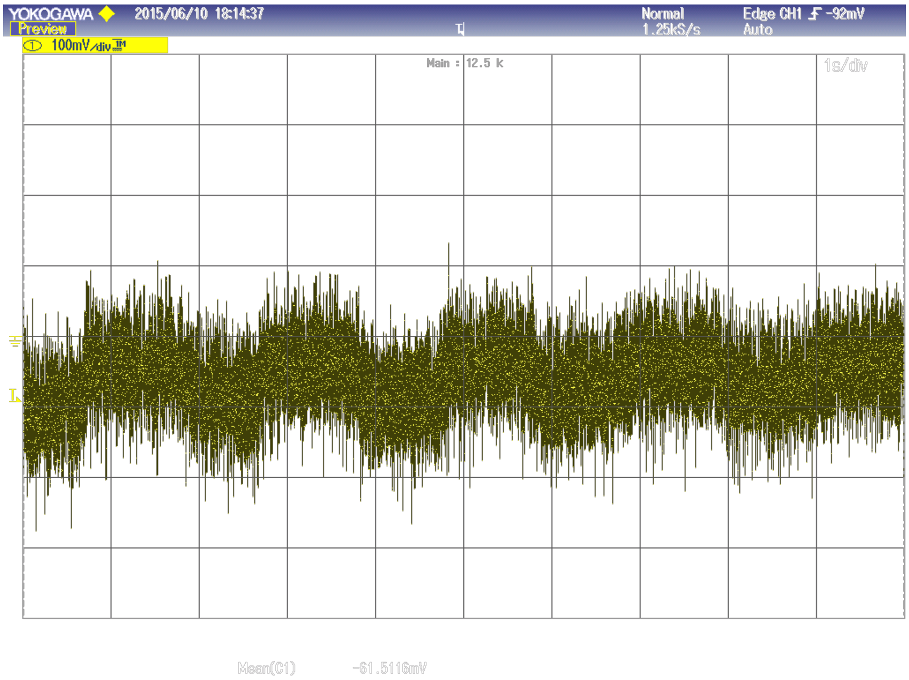


Figure 7.1: Result of the first concept, using a white LED in reflection-FS mode

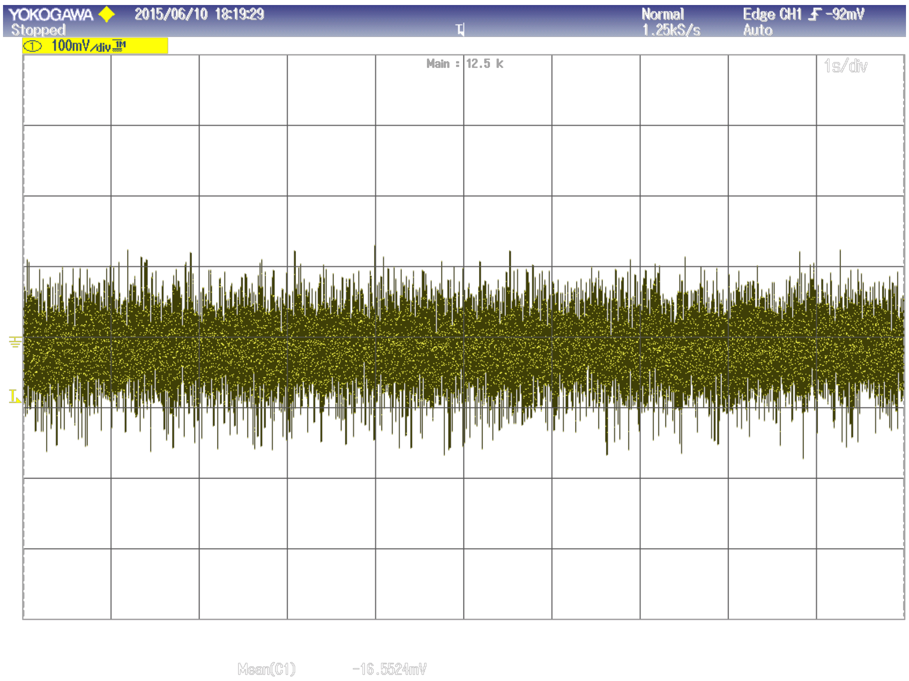


Figure 7.2: Result of the first concept, using a white LED in transmission-FS mode

7.2.2. THIRD RGB CONCEPT

This concept is tested extensively because of the promising results right from the start. The circuit is able to detect minor colour changes (e.g. transmission of light through a piece of leather), and a simulated heartbeat could be measured with this model. Because of these promising results and the discouraging results of the other two approaches, this concept is further examined and the previous versions were not.

The results of the reflected RGB intensities can be found in Figure 7.3. The periodically reoccurring peaks are located as expected. Also, the red colour has the greatest intensity, which is as expected when using a partly red coloured piece of leather. By examining the data more closely, the theory was formed that the peaks were caused by motion artefacts. This idea is more closely examined in Section 7.3. The same motion artefact peaks were observed with a transmission implementation.

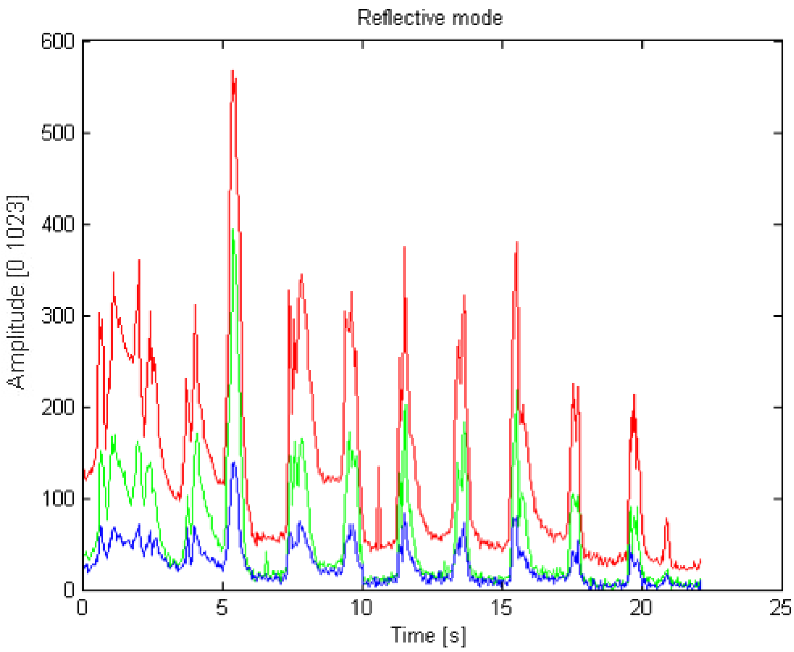


Figure 7.3: Result of the reflection measurement

7.2.3. LDR CONCEPT

Figure 7.4 depicts the result of the first LDR measurement. When ignoring the high peaks, the result resembles a square wave. The amplitude difference is related to the colour difference of the used leather. The occurring peaks are probably motion artefacts, just as in Figure 7.3, and will be discussed in the next section.

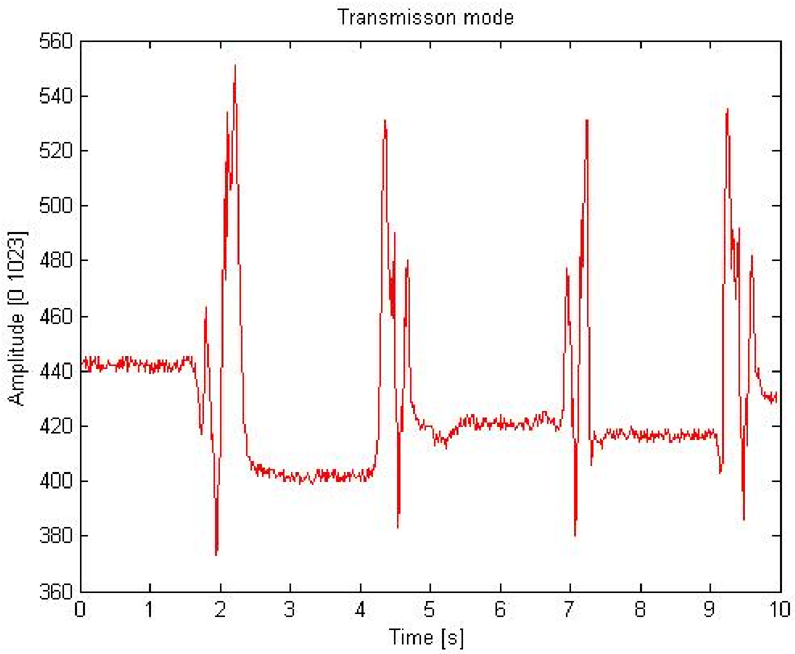


Figure 7.4: Result of the LDR measurement

7.3. MOTION ARTEFACTS

After the first measurement results, discussed in Section 7.2, it was suspected that the peaks were possibly motion artefacts. To detect whether this was the case, an extra input signal was added. This reference signal is used to indicate the time window in which no motion occurs. This signal is generated by a simple pushbutton. If the reference signal is high, the sensor and LED were not in motion, so during this period of time the setup was steady. Therefore, the data recorded during this high time is not influenced by movement. During the low part of the reference signal, the sensor and LED were in motion (from the red piece of leather to the natural coloured leather or back), which can result in motion artefacts. These motion artefacts can be clearly seen in Figure 7.5.

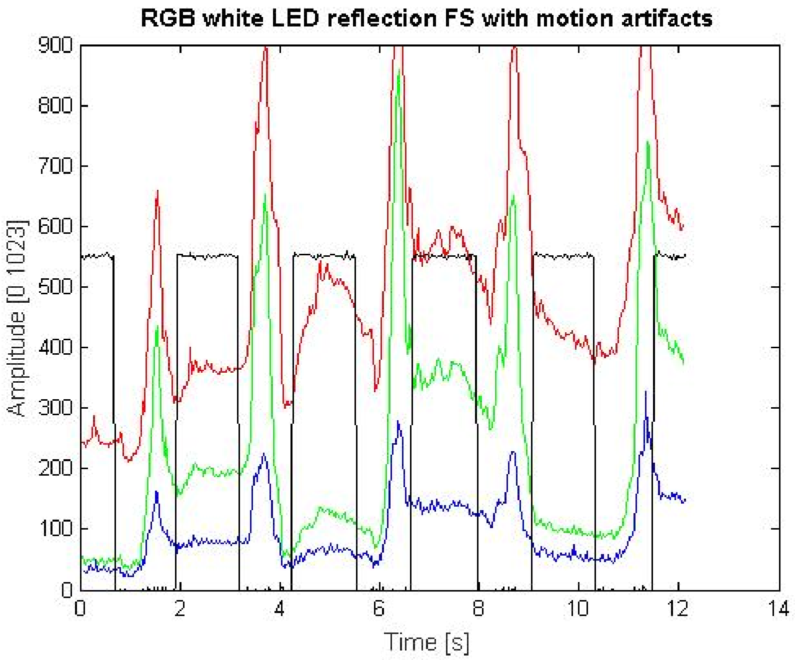


Figure 7.5: Result of the reflection measurement with RGB sensor using a white light. Motion artefacts are clearly visible.

7.4. COMPARISON BETWEEN COLOUR VARIATIONS AND GENERAL LIGHT INTENSITY

To show the effect of variations in colour and changes in light intensity, the following reflection FS measurements were done on the different coloured parts of leather (this piece of leather can be seen in Figure 6.1b):

- spectral component measurements of reflected light (RGB).
- Measurements of broad spectrum intensity (LDR).

Figure E.1 and Figure F.1 in the appendices show the same general characteristics. The blue leather results in the lowest intensities, both with RGB and LDR measurements. The same analogy is visible when comparing the natural and red coloured leather. Because of this correspondence, the assumption can be made that the light intensities measured by the LDR partly resemble the signals measured by the RGB sensor. No information about the colour can be derived from the LDR data, whereas the RGB sensor does provide this information. Appendix G depicts the colour spectrum at three wavelengths: ~460 (B), ~500 (G), and ~600 (R) nm. This graph is briefly explained:

- red coloured leather: the blue RGB component is very low. Green is slightly larger and the red component is by far the largest, which is as expected because the leather is coloured red in this scenario.
- Natural coloured leather: the overall intensity is larger, so a brighter coloured is expected. Also, the spectrum contains mainly green and red colours, resulting in a yellowish colour.
- Blue coloured leather: the relative dark colour is hard to detect, resulting in low intensities.

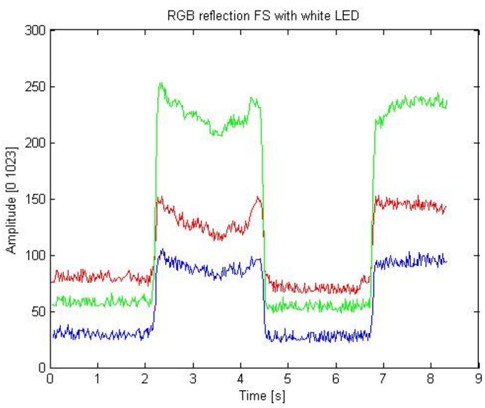
According to the RGB data of the spectral components, the actual leather colours can be estimated. This information cannot be derived from the received LDR data.

7.5. RGB RESULTS

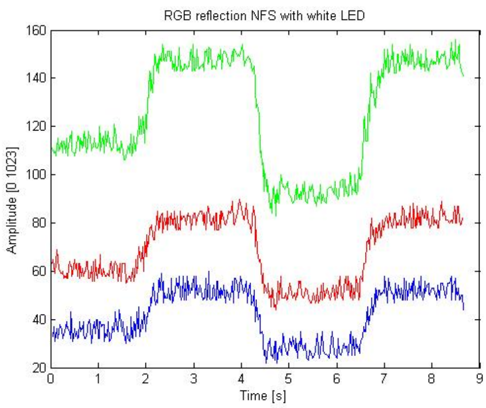
The results of the RGB measurements (using the circuit shown in Figure 6.3) are shown in Figure 7.6 and Figure 7.7. An immediately obvious observation can be made about the difference in reflection and transmission measurements. With either white or red LED, the transmission mode has much more noise than the reflection measurements. When keeping in mind that the heartbeat sensor has to be implemented in a headphone, a reflection measurement is more practical and also yields a better result. The results with a red LED can be found in Appendix H.

When the white LED reflects on a red piece of leather, ideally only red light returns. The red filter of the sensor does not have the exact same colour as the red leather, so the red leather reflects slightly different frequencies of light than the colour sensor could optimally detect. It is thus far more useful to look at the whole spectrum. This property can be seen in Figure 7.6a. At first, the sensor is placed on top of the red part. Here, red light has the greatest intensity. After moving the sensor to the natural coloured part, green light has the highest intensity and red light is much smaller. So, by looking at the whole colour spectrum, a large difference between the two leather colours can be observed. The same observations can be made with the more realistic NFS measurement. These amplitude differences were respectively 25, 40 and 40 bit levels, for the red, green and blue channel.
The other possible setup uses transmission. In this case, the transmitted light through the red part of leather will have a lower red intensity than at the natural coloured leather. Light passing through the natural coloured leather will have a larger red intensity relative to the green intensity. The results can be found in Figure 7.7a.

During the transmission measurement with the sensor facing the partly coloured side of the leather, the LED faces the 'clean' side. Because the red LED transmits (almost) monochromatic light, only this frequency can reach the sensor. This beam of light reaches the leather and a large part will be absorbed by the natural coloured leather. In fact, so much is absorbed that very little light reaches the back of the leather, where the sensor is located. As seen in the result (Figure H.2a in the appendices), the amount of transmitted light is very small, so the difference between red and natural leather is undetectable.

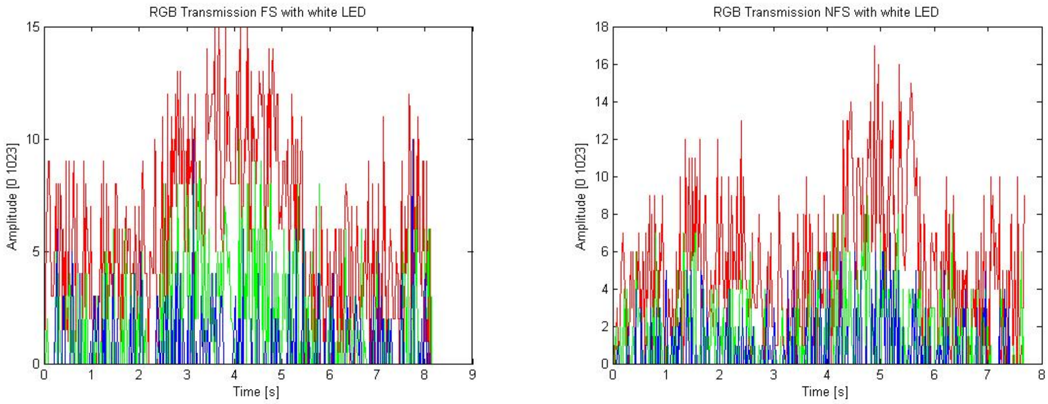


(a) RGB reflection FS



(b) RGB reflection NFS

Figure 7.6: Result of the concept reflection measurements using a white LED



(a) RGB transmission FS

(b) RGB transmission NFS

Figure 7.7: Result of the concept transmission measurements using a white LED

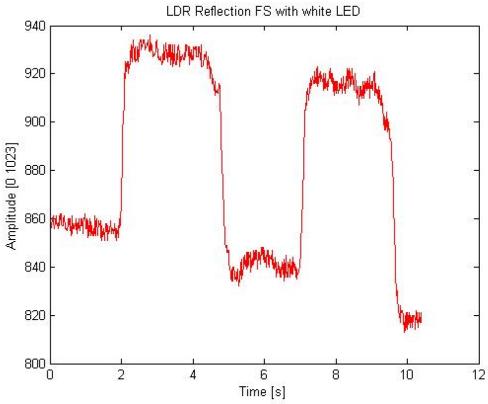
7.6. LDR RESULTS

By using a piece of leather as a rougher model (discussed in Subsection 6.1.3), a few basic properties of the LDR and the leather can be determined. The LDR, in contrast to the RGB sensor, detects intensity changes in the whole spectrum. When placing the LDR on top of the red LED, it detects the intensity of all the light, not just the red light. As a first measurement, this principle is tested in the following two ways:

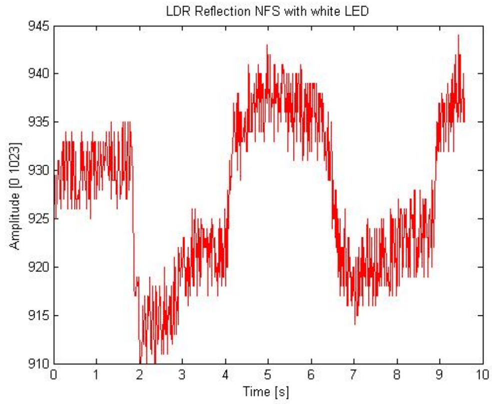
- the leather is placed below the LDR sensor (FS and NFS) with the red LED next to the sensor. The reflection of the red/natural coloured leather is measured.
- The red LED is placed on the other side of the leather (FS and NFS). The transmission of light is measured.

When measuring the difference in reflected light of the red and natural part of the leather, it is expected that the red part reflects exclusively red light (that is why this red colour can be seen). Therefore, the expected intensity is lower at the red part, as the natural part reflects more colours.

When measuring the light reflecting on the red and natural leather, light intensity variations can be detected. These results, using a white LED, are depicted in Figure 7.8 and Figure 7.9. A difference in amplitude (a maximum difference of ~110 bit levels), caused by the colour change of the leather, can be clearly detected. The results of the setup where a red LED is used, are shown in Appendix I.

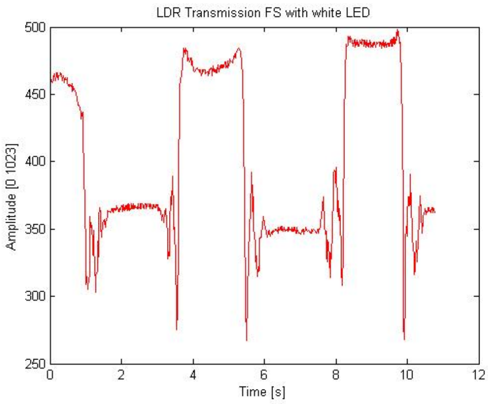


(a) LDR reflection FS

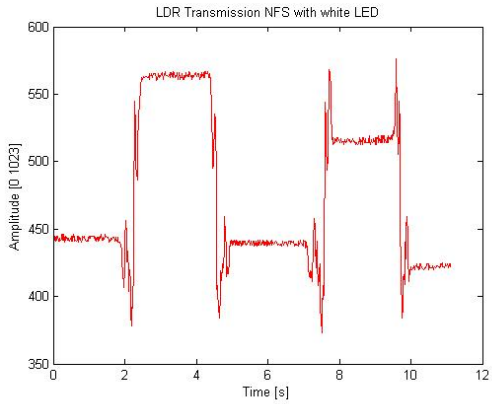


(b) LDR reflection NFS

Figure 7.8: Result of the concept reflection measurements using a white LED



(a) LDR transmission FS



(b) LDR transmission NFS

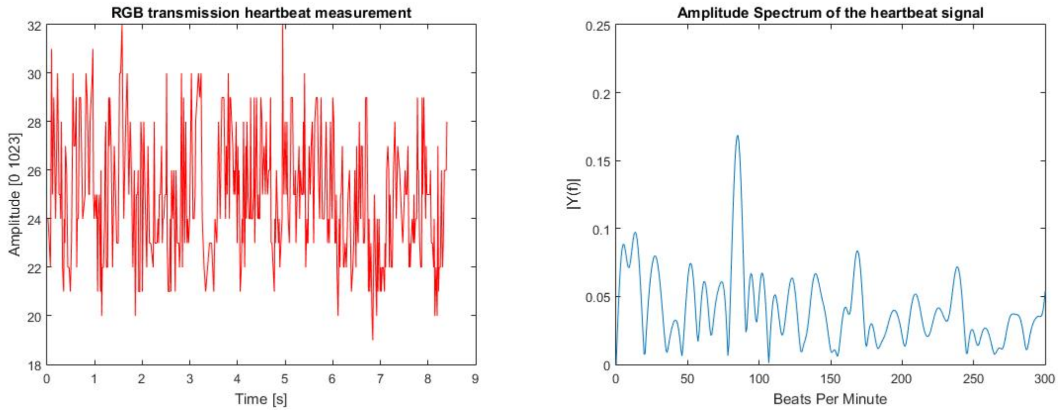
Figure 7.9: Result of the concept transmission measurements using a white LED

7.7. IN VIVO

After the concepts proved to be valid options, real heartbeat measurements were done. These measurements were done on (or in close proximity to) a human fingertip. This location is chosen because the blood flow can be detected manually when a light source is present. A clear pulse can be identified by the naked eye. To prove the detected BPM corresponds to the actual heart rate, a reference measuring device is used [16].

7.7.1. RGB HEARTBEAT MEASUREMENTS

The concept results of the RGB measurement showed that the circuit is able to detect colour changes. The reflection measurements were much better than the transmission measurements (Figure 7.6 and Figure 7.7). Therefore, reflection measurements were expected to yield a better result. After measuring both reflection and transmission, it was clear that only the transmission measurement gave some sort of result (depicted in Figure 7.10). Because of this result, it is possible the implemented model has different properties than human skin. In Figure 7.10a, a waveform could be detected when looking more closely. Figure 7.10b shows a peak at 80 BPM, which was approximately the same as the reference heartbeat measurement. The reflection measurement did not contain any information which could lead to a heartbeat signal, and is therefore not depicted.



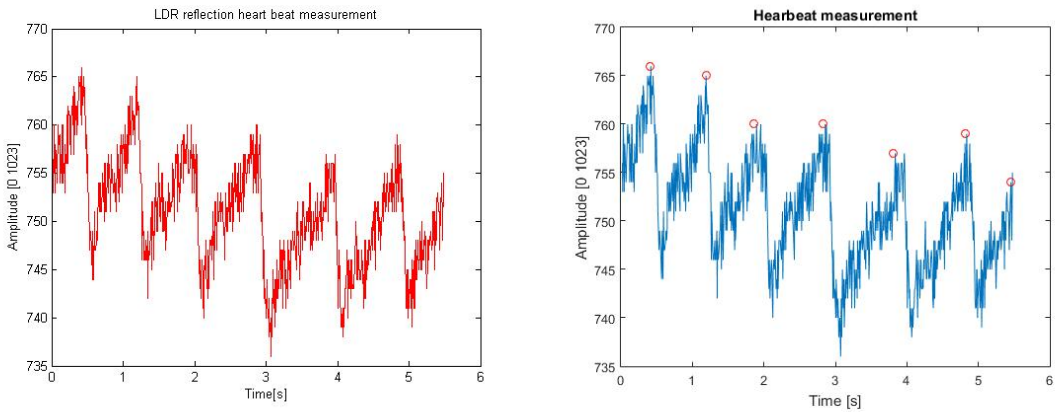
(a) Heartbeat measurement (b) Heartbeat FFT: 85 BPM

Figure 7.10: Result of the RGB transmission measurement of the heartbeat in a human finger (white LED)

7.7.2. LDR HEARTBEAT MEASUREMENTS

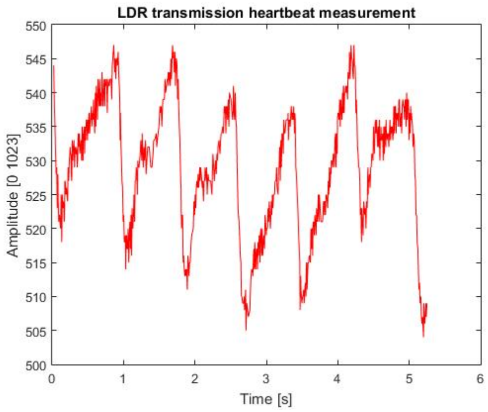
The LED (white or red) was placed on a flat surface. With the reflection measurement, the LDR was placed next to it. When placing a fingertip on top of the LED and in very close proximity to the LDR, the light intensity is measured. As discussed earlier, when the fingertip is closely observed while being partly illuminated by the white LED, a periodical change in skin colour can be observed. This discolouration was measured and depicted as a graph in Figure 7.11a. Figure 7.11b shows the result of the peak-detection algorithm. It is not required to place the finger tip directly on the LED or sensor, but it will give the best result. When used in a bright room, the ambient light will disturb the measurement if the finger is not placed in close contact with the LDR.

The transmission measurements were done in the same way, except the sensor was placed on the other side of the finger tip. The result can be found in Figure 7.12a. The result of heartbeat detection using a FFT filter is depicted in Figure 7.12b. As can be seen in Figure 7.11b and Figure 7.12b, both algorithms are able to detect the heartbeat. The results of the detected heartbeat using a red LED can be found in Appendix J. All the measurements were done in a relatively dark room and validated by a second heartbeat measurement device [16].

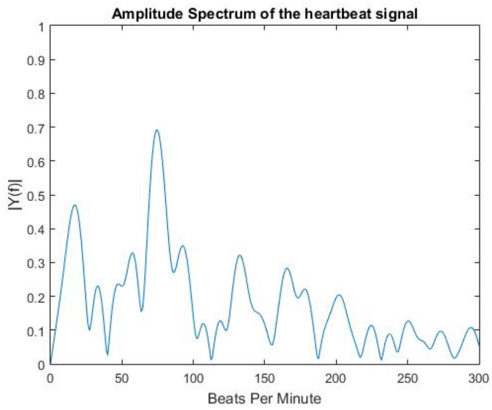


(a) Heartbeat measurement (b) Heartbeat peak detection: 74 BPM

Figure 7.11: Result of the LDR reflection measurement of the heartbeat in a human finger (white LED)



(a) Heartbeat measurement



(b) Heartbeat FFT: 74 BPM

Figure 7.12: Result of the LDR transmission measurement of the heartbeat in a human finger (white LED)

HEARTBEAT MEASUREMENTS AT DIFFERENT DISTANCES

All the LDR (in vivo) measurements discussed so far are done by placing the sensor directly on a fingertip. Chapter 3 states demand 3.2: the possibility to implement the design in the ear. In the final application, the possibility exists that the sensor will occasionally lose skin contact. Therefore, transmission measurements with the sensor at different small distances were done. The sensor is placed up until 1 cm apart from the fingertip. The results can be found in Appendix K. As expected, the intensity of the signal at 1 cm is lower than the measurement at 1 mm. Other measurements were done between 1 mm and 1 cm and yielded approximately the same results. It was detected that the maximum distance to detect a heartbeat (by transmission) was slightly above 1 cm.

From the performed measurements, the conclusion can be drawn that the maximum distance to detect a heartbeat with a reflection measurement is approximately a few millimeters. These results can be found in Appendix L. A possible explanation for the need of close proximity in the reflection mode is that most of the light travels through the skin, as can be observed manually.
As can be seen in the before mentioned figures, a large peak in the FFT can be detected around 0 Hz. This noise artefact peak will disturb the heartbeat peak detection. A algorithm can be written to filter out unrealistic peaks (for example everything outside 0.5-4 Hz).
The measurements were performed with a white LED. Usage of a red LED did not result in a usable heartbeat signal and the results are therefore not included in this thesis.

8

Conclusion

The goal of this project was to examine the possibility to use a colour sensor to detect colour changes, caused by heartbeats. In order to do so, a proof of principle was implemented and tested, after which the step to *in vivo* measurements was made. The results of the proof of concepts and further setups will be discussed in this chapter. Thus far, the main goal (demand 3.1) was achieved, as the heartbeat detection by colour was researched and it can be concluded that this type of measurement is possible. The second demand (3.2) was that measurements in the ear must be possible, i.e., the sensors and LEDs should fit inside the ear. The LDR and RGB sensor are small enough to be implemented in the ear, even in combination with the required LEDs. According to this demand, the entire system should fit in the current design of the headset. Therefore, choices must be made about the measuring device and processing. The Arduino UNO will not fit in the headset, however, smaller Arduino's exist, which can also be used. Another option would be the use of a different ADC. The final requirement (3.3) states the demand of sending the acquired data via a bluetooth link. This feature is not directly implemented, but the possibility exists.
Furthermore, there were preferences that had to be considered. In the following sections, the design choices and best setup are described. In this comparison, only NFS measurements are discussed as they are the most realistic scenario. The rest of the preferences in Chapter 3 were taken into account while making the optimal design choices.

Sensors: LDR or RGB

During this project, two different sensors were compared: an LDR and an RGB sensor.
The LDR concept circuit detects the colour changes of the leather. The best concept measurement was the transmission measurement with a white light source. The difference in amplitude was approximately 110 bit levels (~550 mV). The heartbeat measurements on the fingertips were also most successful when using a white LED transmission setup: around the 25 bit levels (~125 mV). Even the determination of the heart rate at a small distance was best detected by the transmission measurement with a white light source.

The RGB concept showed the best results for the reflection measurement (Figure 7.6b). This concept uses an asynchronous supply, as stated in preference 3.4. The average bit level differences for the NFS measurement were respectively 25, 40 and 40 for red, green and blue. Because of the lower induced current of the blue filtered photodiode, this signal is multiplied by two in this calculation (discussed in Section 6.1). *In vivo* measurements were inconclusive: the transmission setup occasionally yielded results, where reflection mode had no viable results at all.

To compare both methods, a couple of factors will be discussed, starting with the complexity of the setups. The LDR can easily be read out, whereas the RGB sensor requires a more complex circuit. Therefore, the LDR setup has an advantage. Both implementations use an asynchronous supply, in accordance with preference 3.4. While the RGB sensor has the ability to measure the spectrum in three independent segments and compare these spectral components, the LDR still yields a better outcome. When the LDR and RGB concept results are taken into account, the LDR setup is clearly preferable. In addition to these factors, the *in vivo* measurements also point to the LDR setup as being the better option. The final advantage of the LDR are the smaller motion artefacts.

DIRECTION: REFLECTION OR TRANSMISSION

As mentioned above, the best sensor type to measure a heartbeat is an LDR. The reflection and transmission measurements, discussed in Chapter Section 7.6, show both approximately the same bit-level variations in *in vivo* measurements. In the concepts this result was sometimes rather large, but the colour change could still be clearly detected in both implementations. To implement the sensor in the current headset without altering the design (demand 3.2), a reflection setup is most convenient. Taking these two considerations into account, the best measurement for this setup is reflection.

LIGHT SOURCE: WHITE OR RED LED

Two light sources were used in this research project: a white and a red LED, respectively 3.4 and 1.5 cd. Because of this difference in light intensity, the results could not be immediately compared. The result of the intensity measurements at different distances (Appendix K) show the decrease of intensity of the red LED relative to the white LED at further distances. The white LED consumes almost 50% more power to induce this light. This power consumption is more important than the absolute light intensity. Both LEDs were able to light up the fingertip enough to detect the discolouration of skin. Chapter 3 states preference 3.5: the system must have minimal power consumption so the battery life of the headset won't be reduced dramatically. When only considering this preference, a conclusion could be made that the red LED is most suited for this sensor. But, measuring the heartbeat at small distances from the skin wasn't possible with a red light source. When keeping in mind that this sensor has to be implemented in a sports headset (Appendix A), loss of contact is a possible occurrence because of motion. Therefore, despite of the higher power consumption, the white LED is concluded to be the best light source for heartbeat reflection measurements.

PEAK DETECTION: FFT OR TIME-DOMAIN

To derive the heart rate from the acquired data, two algorithms were discussed. The major disadvantage of the time-domain algorithm are the multiple peaks. When motion artefacts occur, a motion peak is easily mistaken for a heartbeat, resulting in a flawed result. By using FFT, the effect of these artefacts is smaller, as the only harmful interference occurs in a specific frequency band (0.5 - 4 Hz). In accordance with these observations, FFT is the most suitable heart rate detection method.

SIMULATION VALIDITY: MODEL VERSUS *in vivo*

Section 7.5 reveals a better result in the concept measurements for reflection than transmission. However, as discussed in Section 7.7, the only viable heart rate measurement was obtained using transmission. These differences between the concept and the *in vivo* measurements show that, for the RGB setup, the used leather (Figure 6.1a) did not have the same reflection and transmission properties as human skin. However, the properties of the leather did correspond to human properties in the *in vivo* LDR measurements, which were well above the expectations.
Because the model did resemble the human skin measurement results and the LDR setup has already been identified as the most promising configuration, the conclusion can be made that the rougher model is a good representation of the human skin in this setup.
During the *in vivo* measurements, the heart rate was concurrently monitored with a reference device. The gathered *in vivo* results correspond to the reference measurements.

Using an LDR in combination with a white LED has been proven to be the best method to detect skin discolouration due to heartbeats. Processing this data with an FFT results in the most accurate heart rate detection.

9
Discussion and Future Recommendations

This thesis concludes eight weeks of research and development. The project may be continued in the future by the Delft University of Technology, and therefore, some recommendations will be done. A couple of concept circuits were tested and one was discovered to be the best. These circuits may be slightly altered in the future to re-evaluate their effectiveness. They can also be perfected in terms of power consumption. Another option would be to use a different colour sensor, either with higher precision or a digital sensor. This different sensor might improve the colour data in such a way that the colour differences can be used in stead of the intensity difference. In the colour differences, much more information may be concealed, which can be investigated with a better colour sensor.

In order to improve precision, a different measuring device can be chosen. An ADC with more bit levels can be used, or the ADC of the Arduino can be fine tuned to better match the voltage range of the input signal. In this way, the minimal detectable voltage difference can be reduced and more information about the heartbeats may be gathered.

The LEDs used in this research project emitted light at different intensities. Both light sources (red and white) were able to illuminate the model or fingertip enough, but real comparisons could not be made. In the future it would be recommended to implement (smaller) LEDs with the same intensities or power consumption, so a proper comparison can be done to identify the most suitable light colour. To further minimise the LED size, the minimum light intensity needed to still detect a heartbeat could be investigated (therefore lowering the energy consumption). In Chapter 8 the conclusion was made that a white LED was most suitable for the reflection heartbeat measurements. This conclusion was mainly based on the precedence that the setup uses a LDR. When using a RGB sensor to detect colour variations, a white LED must be used in order to make use of all the spectral information.

During the project, *in vivo* measurements were done. But all these measurements were done on fingertips instead of the ear; the intended location for heartbeat measurements. Because of time limitations, ear measurements were not further researched in this project. It is proven that it is possible to measure the heart rate colour variations on the human skin. Future studies can use these results to design and configure the next step to detecting a heartbeat in a human ear by skin colour changes.

A piece of leather was used, as this was thought to be the closest match to human skin. However, the optic properties of the model were not thoroughly investigated, resulting in some differences between the concept and *in vivo* measurements. To better understand the specific optics, a couple of important measurements could be done. The response of both sensors to the specific LEDs is an important factor. This could be measured by more precise optical measurements. Other aspects include angle of incidence and reflection, and beamforming of light.

Two different methods were discussed to extract the heart rate from the measured data. A simple peak detection was used, but the preferred method utilises an FFT. Both methods can be improved: the peak detection could include filtering. The bandwidth that will be examined by the FFT can also be reduced by filtering. A hybrid detection method could be implemented in the future, a combination of both FFT and time domain data, which could perhaps reduce motion artefacts. Another option would be to use cross-correlation between the R, G an B channels to filter motion effects.

Abbreviations

BAP	Bachelor Afstudeer Project
BPM	Beats Per Minute
FFT	Fast Fourier Transform
FS	Facing the Sensor
GUI	Graphical User Interface
LDR	Light Dependent Resistor
LED	Light Emitting Diode
NFS	Not Facing the Sensor
PPG	Photoplethysmography
RGB	Red, Green, Blue

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A

BackBeat FIT

Figure A.1: The current BackBeat FIT

B

Graphical User Interface

Please Turn Over

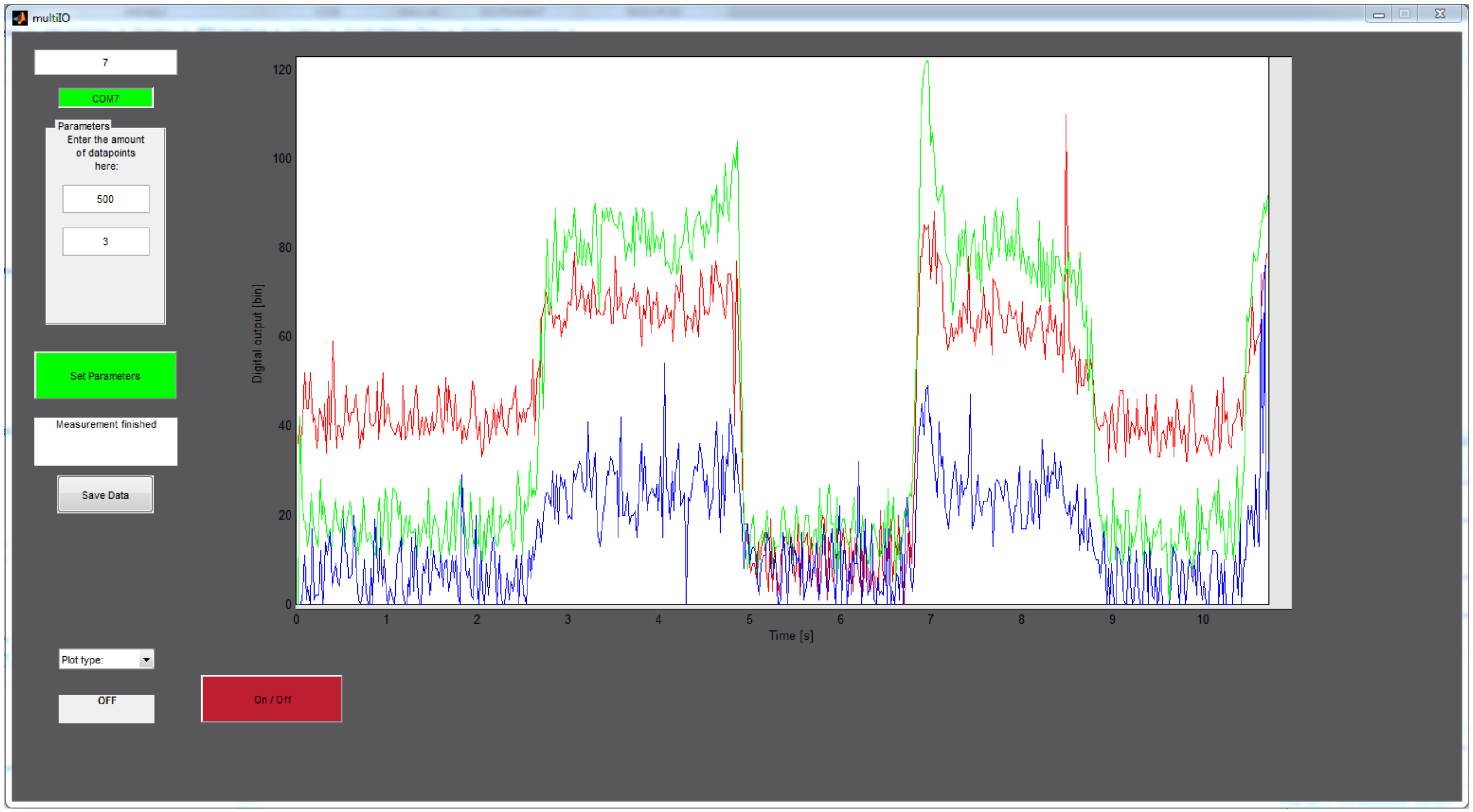
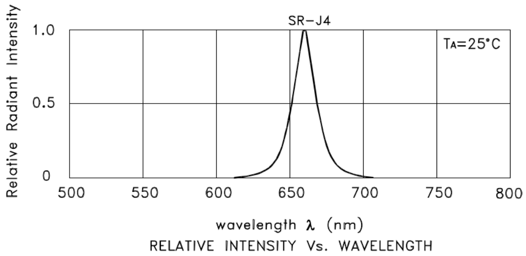


Figure B.1: The Graphical User Interface

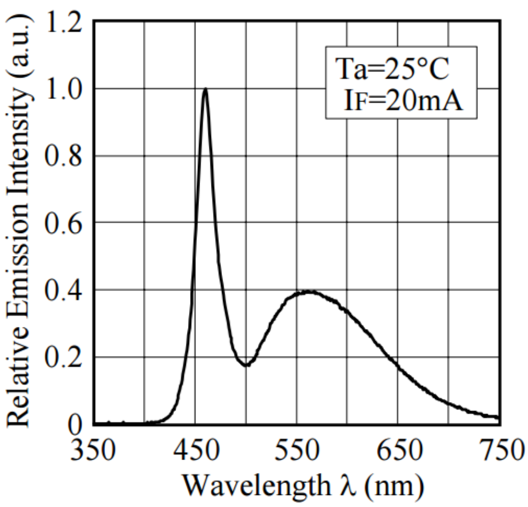
C

Spectral properties of the used LEDs and sensors

These graphs were provided in the datasheets [17], [21], [22].



(a) Red LED



(b) White LED

Figure C.1: The spectral components of the different LEDs

There is no spectral information provided for the LDR, only the peak wavelength, which is 550 nm.

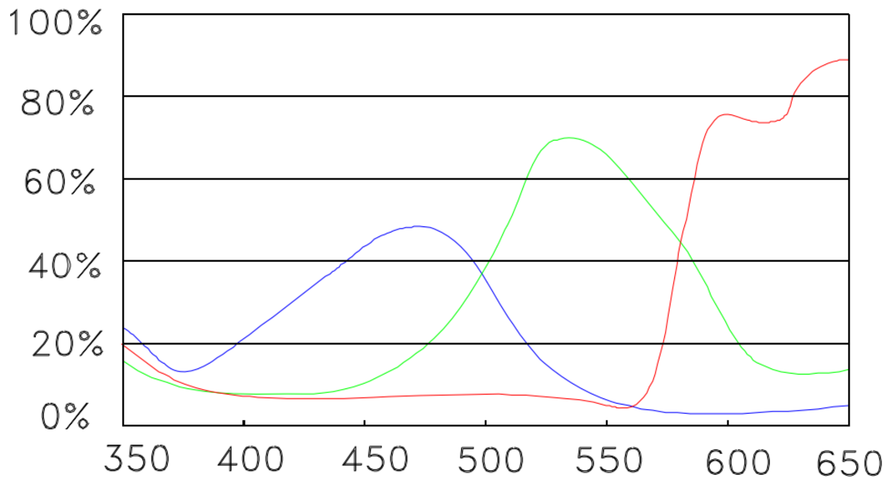


Figure C.2: Spectral sensitivity of the RGB sensor

D

LED CALIBRATION

Please Turn Over

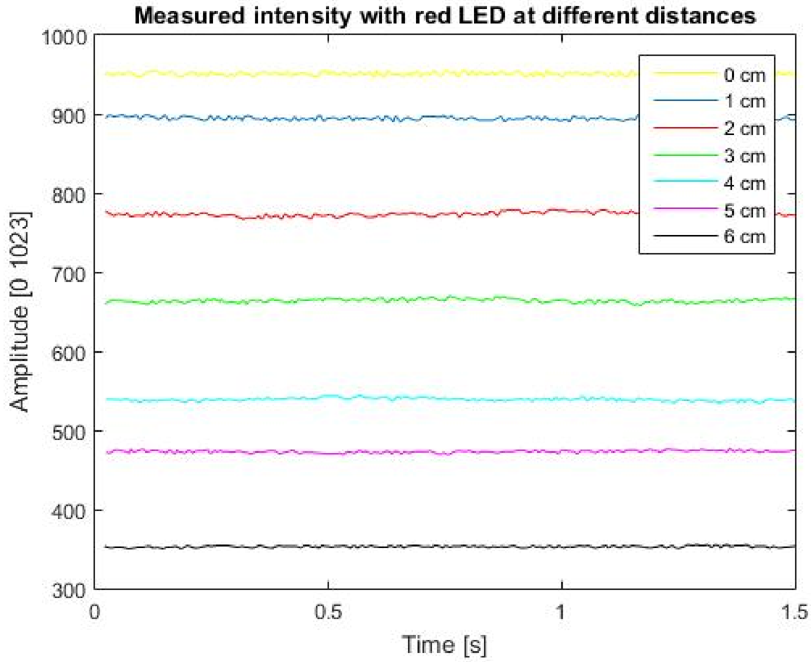


Figure D.1: Distance measurement using a red LED

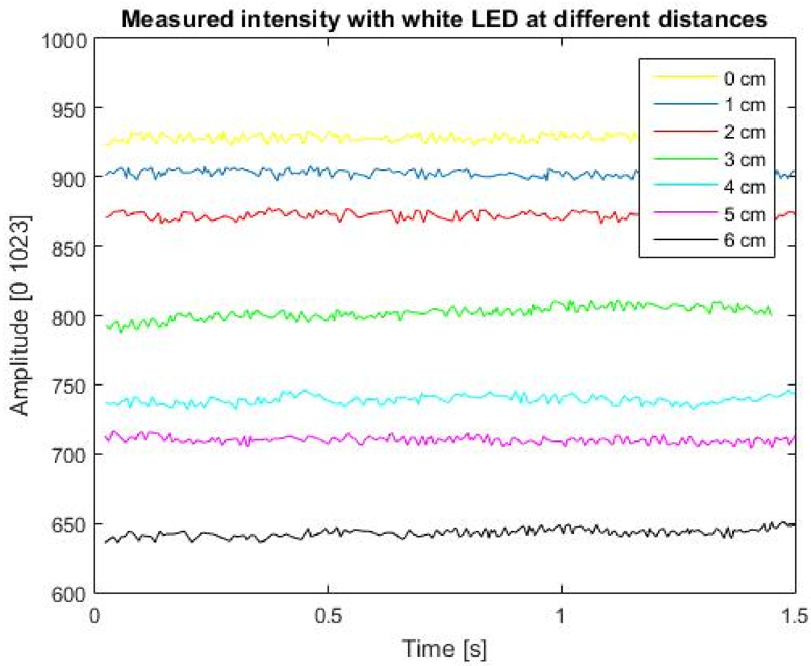


Figure D.2: Distance measurement using a white LED

E

LDR MEASUREMENT WITH ALTERNATING LEATHER COLOUR

Please Turn Over

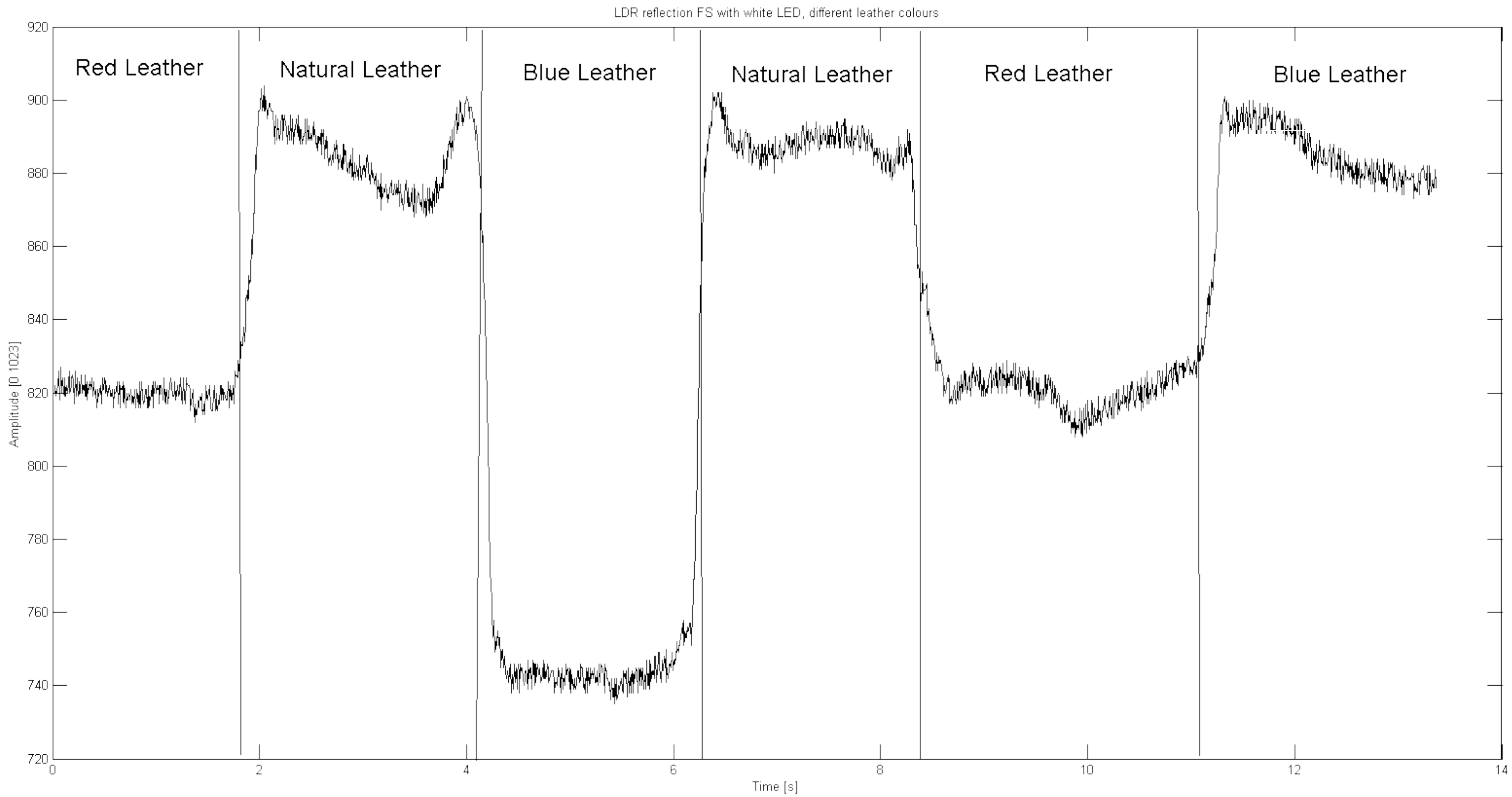


Figure E.1: Results of the LDR reflection FS measurement with three leather colours (white LED)

F

RGB MEASUREMENT WITH ALTERNATING LEATHER COLOUR

Please Turn Over

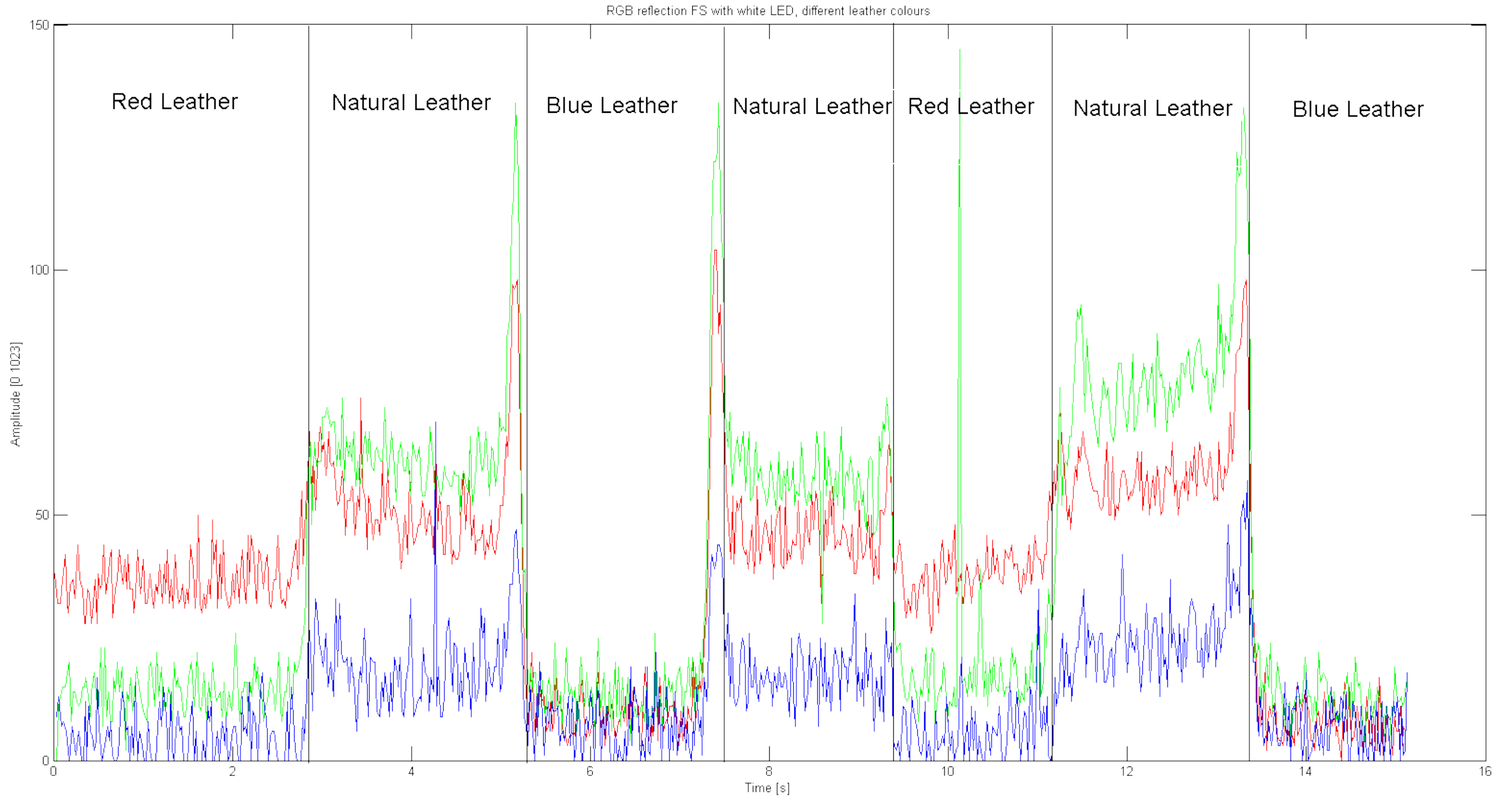


Figure F.1: Results of the RGB reflection FS measurement with three leather colours (white LED)

G

SPECTRAL COMPONENTS USING THREE TYPES OF COLOURED LEATHER

Please Turn Over

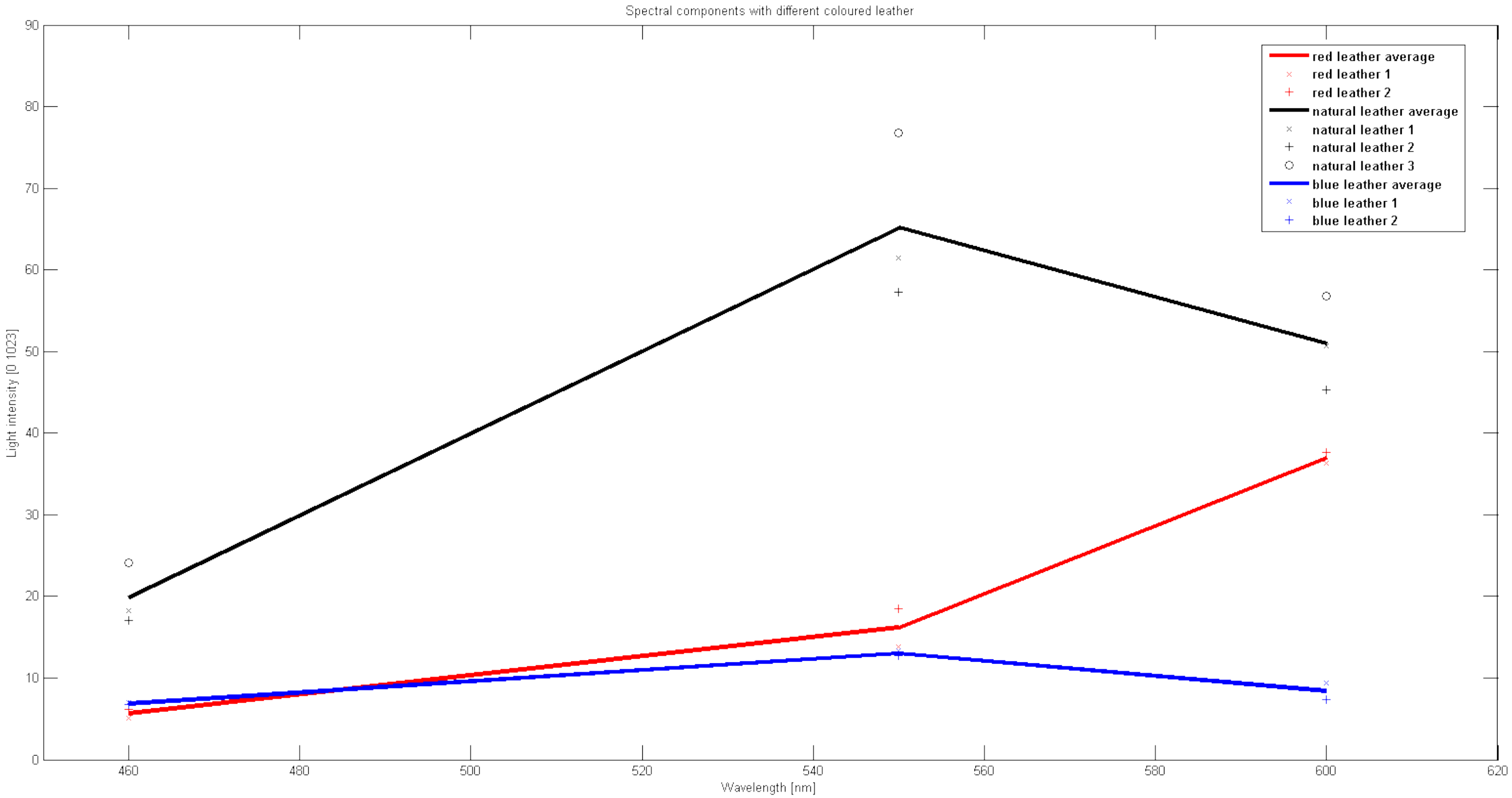
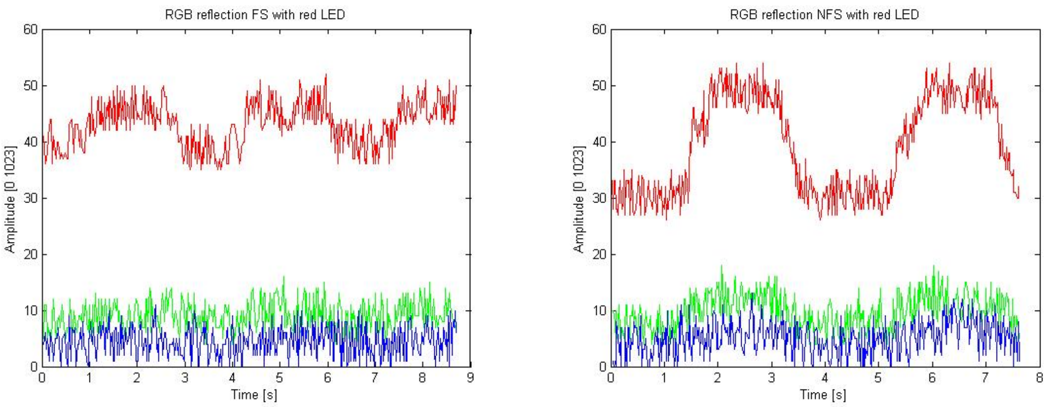


Figure G.1: Spectral components of the three leather colours using a white LED

H

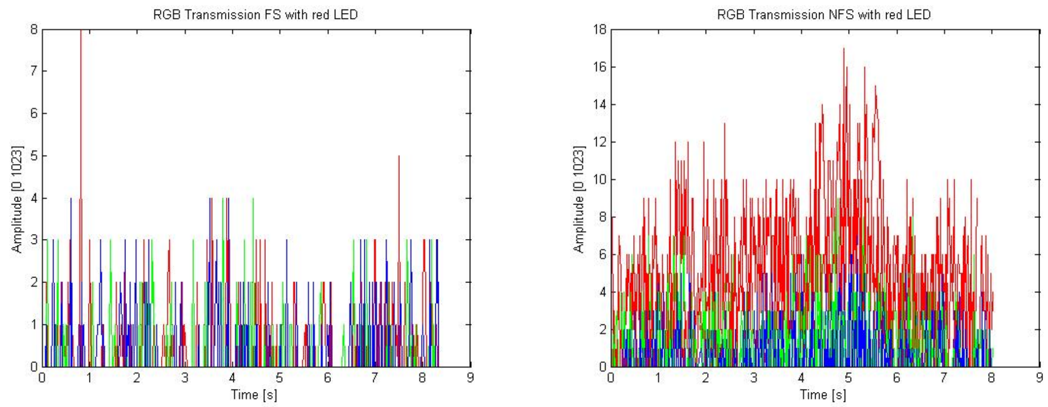
RGB CONCEPT RESULTS WITH A RED LIGHT SOURCE



(a) RGB reflection FS

(b) RGB reflection NFS

Figure H.1: Result of the concept reflection measurements using a red LED



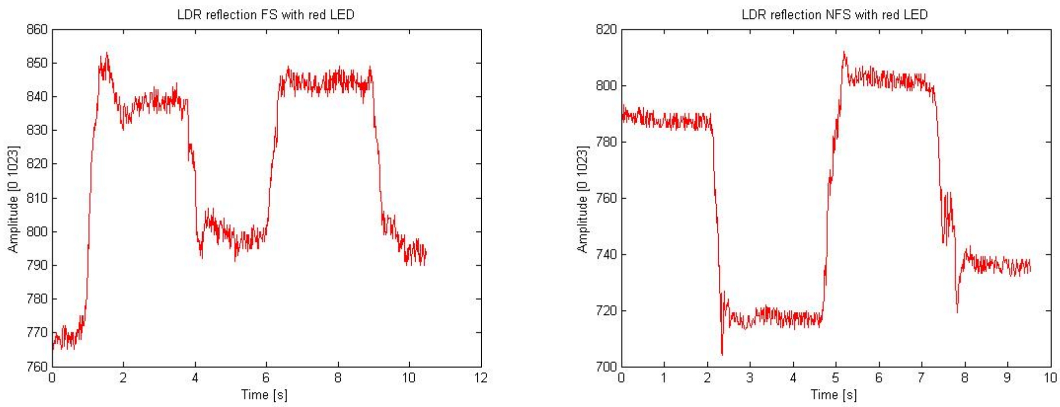
(a) RGB transmission FS

(b) RGB transmission NFS

Figure H.2: Result of the concept transmission measurements using a red LED

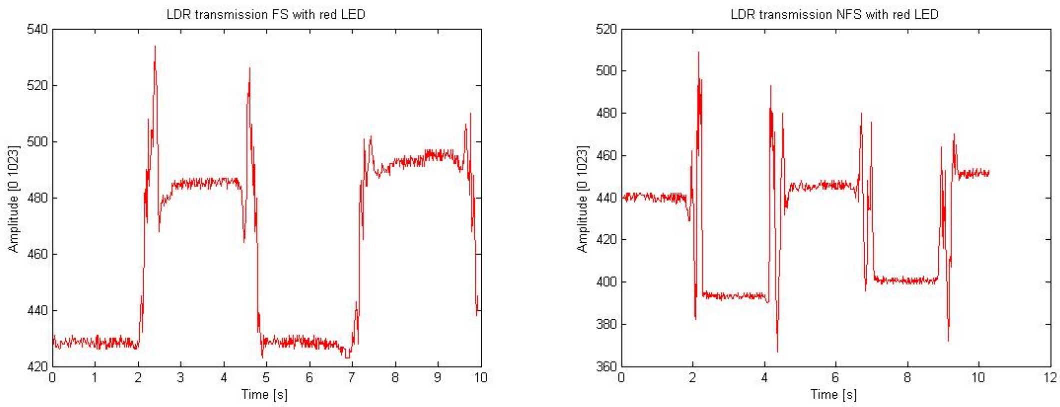
I

LDR CONCEPT RESULTS WITH A RED LIGHT SOURCE



(a) LDR reflection FS (b) LDR reflection NFS

Figure I.1: Result of the concept reflection measurements using a red LED

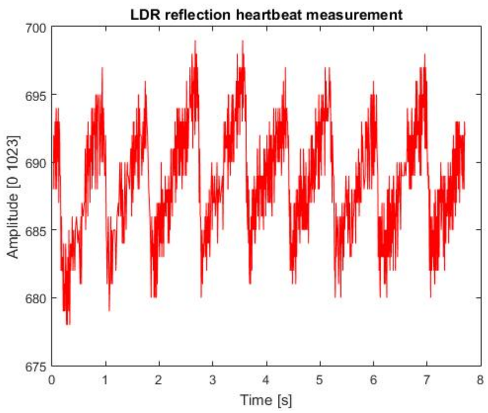


(a) LDR transmission FS (b) LDR transmission NFS

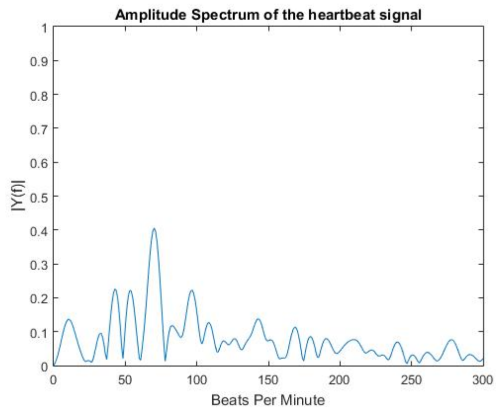
Figure I.2: Result of the concept transmission measurements using a red LED

J

IN VIVO: LDR WITH A RED LIGHT SOURCE

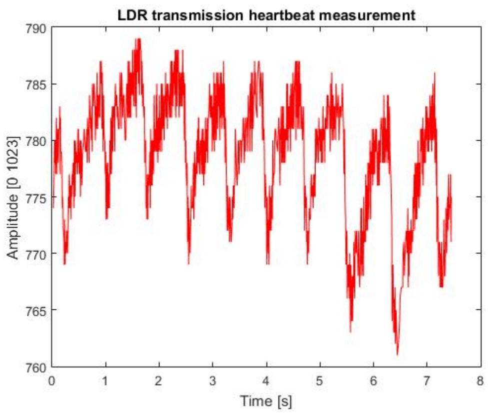


(a) Heartbeat measurement

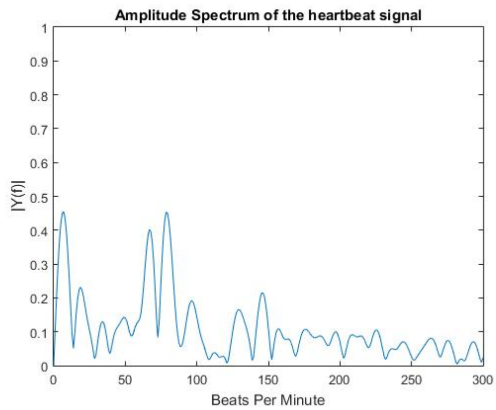


(b) Heartbeat FFT: 70 BPM

Figure J.1: Result of the LDR reflection measurement of heartbeat in human fingertip (red LED)



(a) Heartbeat measurement

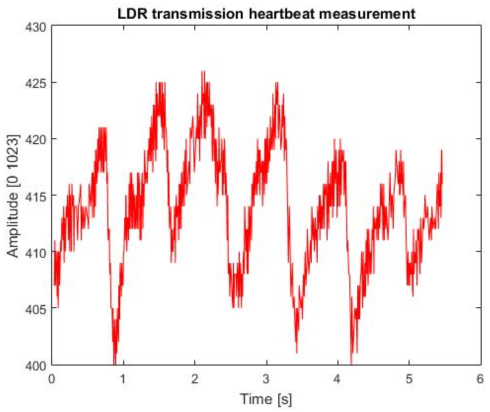


(b) Heartbeat FFT: 79 BPM

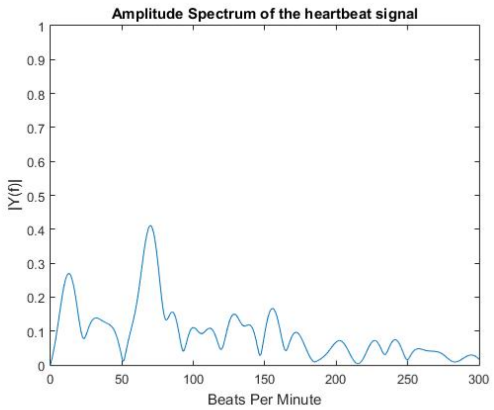
Figure J.2: Result of the LDR transmission measurement of heartbeat in human fingertip (red LED)

K

In Vivo: LDR transmission at different distances

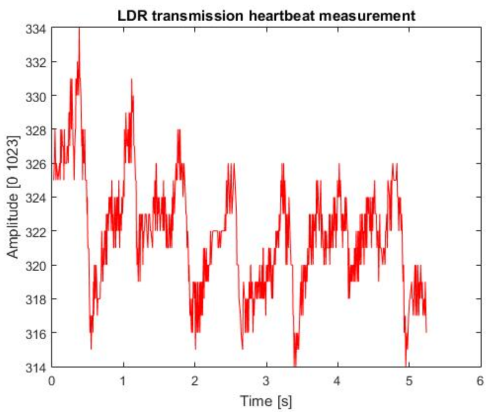


(a) Heartbeat measurement

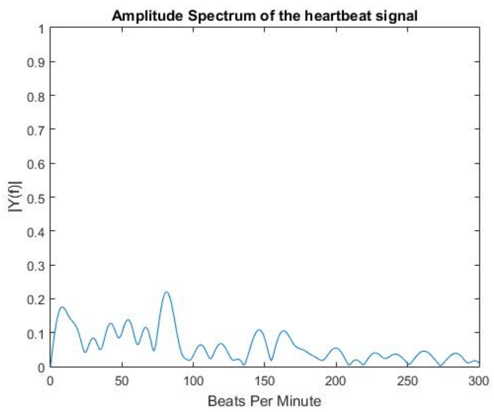


(b) Heartbeat FFT: 70 BPM

Figure K.1: Result of the LDR transmission heartbeat, fingertip placed 3 mm from sensor (white LED)



(a) Heartbeat measurement

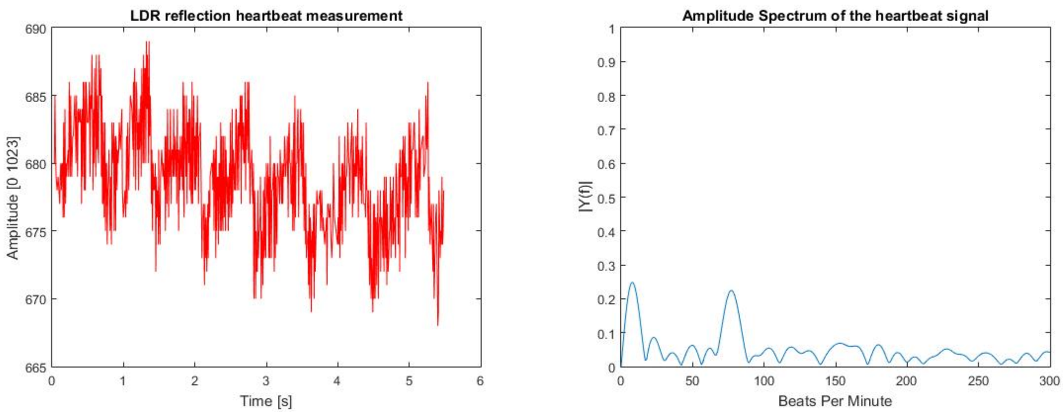


(b) Heartbeat FFT: 81 BPM

Figure K.2: Result of the LDR transmission heartbeat, fingertip placed 1 cm from sensor (white LED)

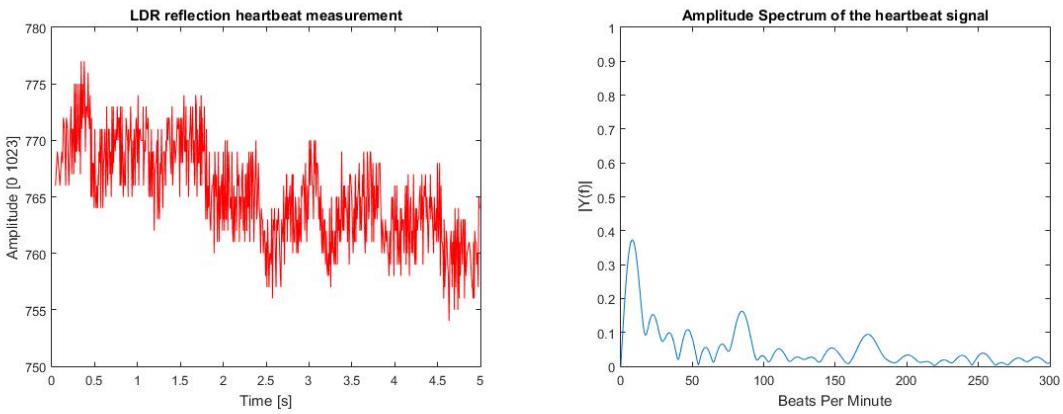
L

IN VIVO: LDR REFLECTION AT DIFFERENT DISTANCES



(a) Heartbeat measurement   (b) Heartbeat FFT: 77 BPM

Figure L.1: Result of the LDR reflection heartbeat, fingertip placed 1 mm from sensor (white LED)



(a) Heartbeat measurement   (b) Heartbeat FFT: 85 BPM

Figure L.2: Result of the LDR reflection heartbeat, fingertip placed 3 mm from sensor (white LED)