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Metropolia Signals Box

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Information Technology

Bachelor’s Thesis

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PREFACE

This thesis represents the end of my studies as an undergraduate student of engineering. It was a long road and, typically for the field of engineering, not always easy, showing once again that every task can result in unexpected challenges.
Still I learned a lot and I am very encouraged to continue my journey in the field of engineering full of curiosity.
At this point I would like to thank my supervisors Antti Piironen and Manfred Jungke for the opportunity to gain some international experience and to finish my bachelor’s degree abroad with an interesting and challenging task.

Helsinki, Finland, 14 August 2018
Lars Georg Schneider

Abstract

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The goal of this thesis was to develop a prototype of the Metropolia Signals Box which can measure several different biosignals through their corresponding potential difference between two electrodes. The signals should then be processed, stored and wirelessly transmitted. In general, this box should serve research and educational purposes.

As a basis of this application the Cyton biosensing board by OpenBCI was examined. The result was that this board covers nearly all required specifications for the Metropolia Signal Box. It can measure EEG, ECG, EOG and EMG signals, amplify and filter as well as store and transmit them. Additionally, it features an accelerometer.

In addition to the features already existing in the OpenBCI GUI, the possibility of temperature measurement was added. For this purpose an already existing part of the GUI was altered, so that it not only reads analog voltage, but converts it directly into the temperature. Two temperature sensors, one providing directly an analog voltage and a NTC thermistor, were used. With the first sensor the temperature can be measured with an accuracy of 1°C, and with the second one it was possible to improve the accuracy to 0.1°C.

Keywords	Electrocardiography, electroencephalography, development, OpenBCI, temperature measurement

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List of Abbreviations

ADC	Analog-to-digital Converter
BLE	Bluetooth Low Energy
BTA	British Telecom Analog
ECG	Electrocardiogram
EEG	Electroencephalography
EMG	Electromyogram
EOG	Electrooculography
FFT	Fast Fourier Transform
GUI	Graphical User Interface
I²C	Inter-Integrated Circuit
Metropolia UAS	Metropolia University of Applied Sciences
NTC	Negative temperature coefficient
OpenBCI	Open Brain Computer Interface
UART	Universal Asynchronous Receiver Transmitter

1 Introduction

This thesis is carried out for the Metropolia University of Applied Sciences (Metropolia UAS) and explores a way of creating a wearable device for effective patient monitoring. Modern medicine uses a lot of different devices to measure various biometric parameters. While this is handy when just one or two parameters should be measured, it can be problematic when many parameters are needed, for example in intensive care. It can soon happen that the patient is burrowed under various cables and tubes and caretakers can have difficulties nursing the patient. Moving this equipment and connecting it with a patient takes time and the devices the sensors are connected with take a lot of room and can therefore not be moved easily or used in every place. Often each manufacturer uses its own connector types so that a sensor cannot be easily connected to devices from different manufacturers.

The Health Technology majoring option of the Information and Communication Technology degree programme at the Metropolia UAS healthcare department is interested in the development of a small and easy-to-use device, which can measure several patient parameters at once. Once having such a device, future healthcare students can use it for developing applications for remotely monitoring body values, such as a smartphone app or web-based applications. This thesis aims at developing a prototype for this device, the so-called Metropolia Signals Box. This box can measure several biometric parameters at once, store them on a SD card and transmit them wirelessly in real time. It preferably uses more general connector types for a more flexible use. Wearability is important, which is why the device should be battery operated and small enough to be carried around with the patient. These requirements are set by the Metropolia UAS.

This research is based on Olli Kortelainen’s Innovation Project, in which research into using an already existing device, Libelium’s MySignals box, was done. The original idea of this project was to improve the MySignals box, so that it fits the requirements set by the healthcare department. After arriving at the conclusion that this box cannot meet those requirements, further research on developing the Metropolia Signal Box using already existing devices like the RaspBerry Pi 3 was done.[1] Using Kortelainen’s findings, a decision will be made which device can be used for developing the prototype or if none of those devices can be used at all. In this case, alternate devices should either be found or developed entirely from scratch.

This thesis is divided into five sections. The first section describes the task for this work, the second section provides a more detailed overview of the project background and some related medical theory and the third section describes the hardware and software used in this project. In the fourth section the project's results are explained and finally in the fifth section a conclusion of the overall process is drawn.

2 Project Background and Medical Theory

This section starts with a summary of the Innovation Project this thesis is based on and the specifications for the Metropolia Signals Box as defined in the first project meeting with the Metropolia representatives. After that, the concepts of electroencephalography (EEG) and electrocardiogram (ECG) are explained.

2.1 Innovation Project *Metropolia Signal Box*

Kortelainen (2017) starts his project report with a research of different devices that may be useful for building a prototype of the box he intends to develop. He starts with the Libelium's MySignals box which has already several biometric sensors and can transmit data. However, he claims that the cons outweigh the pros, as the display size makes the values hard to read and the upload frequency of five seconds is too slow and cannot be altered. [1 pp. 2-3]

Next, Kortelainen investigates the RaspBerry Pi 3, a credit-card sized computer that is capable of everything a desktop computer can do and is easily programmable. It has many general connectors, but due to its processor architecture, it can only be used with sensors whose manufacturers provide suitable drivers. Another con is that the RaspBerry Pi does not support analog input, so the mostly analog sensor outputs would need to be digitalised first. [1 pp. 4-5]

In the next step, Kortelainen reviews the Arduino Leonardo. This is a microcontroller board which allows the user to connect various devices to the microcontroller. It has analog as well as digital connections. In his report he connected a Vernier Shield to the Arduino, because British Telecom Analog (BTA) ports were needed for the sensors. The downsides of this device are that the Arduino cannot be connected directly with the internet and that it is difficult to find appropriate program code for the required functions. The most important downside was that once two sensors were connected to the Shield, the input from the sensor connected first changed. [1 pp. 6-8]

The last device mentioned in Kortelainen's report is a so-called SensorDAQ which can connect BTA ports with a RaspBerry Pi 3 using the corresponding driver. The problem here is that the speed the data is gathered with cannot be modified and the data itself cannot be forwarded to another device or stored. [1 p. 9]

Kortelainen provides an overview of the specification of the Metropolia Signals Box with which he worked. However, these specifications are not as relevant for this thesis as for his review of the different devices, because in the first meeting concerning this thesis with Kortelainen, Sakari Lukkarinen, the project manager from the healthcare department, Antti Piironen, the supervising lecturer, and the author of this thesis a different set of specifications was worked out. These specifications are explained in the next section.

2.2 Metropolia Signals Box’s Specifications

The general idea of the box to be built is that several different sets of sensors can be connected to it and the box then processes their values, stores them on an SD card and optionally transmits those values wirelessly either via Bluetooth or Wi-Fi. Investigation has to be carried out which form of wireless transmission works best. The storage capacity should cover two hours of measuring. Wearability and an easy use of the device are important aspects as well.

In the first project meeting it was decided to restrict the supported non-invasive sensors to the following biometric measurements: Electrocardiogram (ECG), Electromyogram (EMG), Electrooculography (EOG), Electroencephalography (EEG), two temperature sensors for measuring body temperature, and three optical sensors for oximetry and pulse measurements.

At the beginning of the project work, the main focus will be on ECG and EEG measurements, because once the general framework of receiving, processing and transmitting/storing sensor data exists, connecting other sensors is anticipated to be easier. Therefore, it is not necessary to include every sensor type in the project at once. Since it is easier to attach electrodes for ECG measurement to oneself, this will be the initial measurement type to work on.

For a better overview of the specifications, they are additionally listed in table 1. The specifications are numbered for easier reference. However, the numbering does not indicate any prioritisation.

Table 1. Metropolia Signals Box’s Specifications

Number	**Specification**
1	Non-invasive sensors (ECG, EMG, EOG, EEG, temperature, oximetry, pulse measurement)
2	Wireless transmission (Bluetooth or Wi-Fi)
3	Two hour storage on SD card (optional)
4	Wearability, easy to use

The following part deals with the concepts of EEG and ECG measurement.

2.3 Electroencephalography

Electroencephalography visualises the electrical activity of the brain created by neuronal signal exchanges. In order to receive information about these exchanges, electrode couples placed on the scalp measure potential differences and their changes over time. Healthcare uses this form of biopotential measurement for several purposes, e.g. detecting and examining irregularities in the brain activity. [2]

For achieving good EEG measurement results, electrodes need to be placed precisely on the scalp. The signal of these electrodes must then be amplified and filtered and sent to tools for visualising and logging. The way the EEG reading is visualised depends on the used instruments and the desired task. [3 p. 4] In general, waveforms with a paper speed of 30mm/sec (slower for an EEG during sleep) are used for data visualisation. [3 p. 9]

2.3.1 Electrodes

Electrodes serve the purpose of connecting the measurement device with the patient’s head, making a conducting link between a signal input of the device and the corresponding place on the scalp. Although it is possible to use intracellular electrodes for receiving potential differences across cell membranes, only surface electrodes are covered in this section. These electrodes are more commonly used and the scope of this thesis uses non-invasive sensors only. Surface electrodes are placed on the scalp and a conductive gel can be added between the electrode and the head. [2. 3 p. 5]

The electrodes are usually placed on the patient’s head using the international standardised 10-20 system as shown in figure 1.

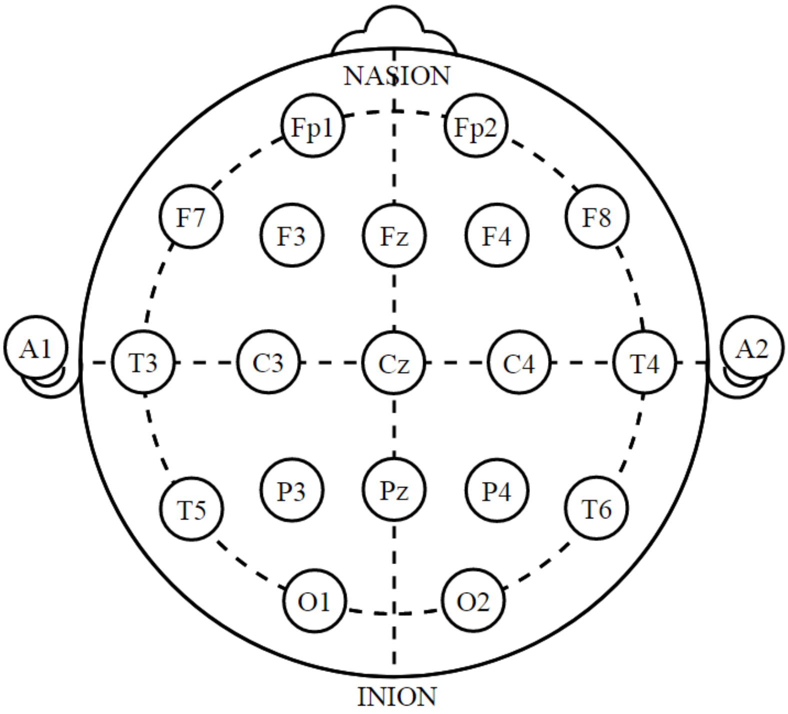


Figure 1. The 10-20 electrode positioning system. [4]

This system uses characteristics of the head as references for the positions of the electrodes. The distance between the electrodes should then represent 10% or respectively 20% of the length of the head measured from the forehead to the back of the head and from one temple to the other. [3 p. 5]

2.3.2 Amplifiers, Filters, and Safety

Electric signals of the brain have normally small amplitudes and therefore must be amplified for proper analysis. The amplitude of the brain activity of an adult is about 10µV to 100µV, so the signal amplifiers in the measuring device need to have a gain between 100 and 100000. Furthermore, they should be able to resolve 0.5µV and support a sampling rate of at least the doubled highest frequency occurring in the wanted measuring scope. [5 pp. 2, 8]

Besides amplifying the signal itself, the amplifier must be able to reduce the impact of noise coming from other electrical devices or the power supply. This purpose requires a high common-mode rejection ratio (the ability to reduce electrical noise on the signal) greater than 100dB and a high input impedance greater than 100MΩ. [5 p. 8]

During an EEG measurement, electric signals from other parts of the body or from other electrical sources can occur. It is necessary to remove these artefacts before the measurement is analysed, since they can lead to false interpretation. As described above, the signal amplifiers already remove parts of these artefacts. In addition, alterable low pass and high pass filters are applied to the signal channels as well as a notch filter for reducing the noise from power lines. [5 p. 8]

Devices used in medical applications must fulfil certain electrical safety criteria. For example, they need to be grounded and electrically insulated concerning both the input and the output in order to prevent electrical shocks or fire caused by short-circuits. This is especially important for the connection with other medical devices. Since the corresponding regulations vary between different countries, a medical device must conform to the regulations of the country in which it is supposed to be used. [6 p. 98]

2.4 Electrocardiogram

An electrocardiogram is used to visualise and record the electrical activity of the heart. This electrical activity is caused by changes in the polarisation of different heart areas, which leads to rhythmic contraction and relaxing of the atria and ventricles. The following sections provide an overview over the electrode placement and visual representation of a regular sinus rhythm in a standard 12-lead electrocardiogram and the setup for an ECG measurement system.

2.4.1 ECG Lead Placement and Diagram

ECG measurement uses a universal positioning system for attaching each electrode on the patient’s body. This ensures that differences between two consecutive ECGs are not caused by different electrode placement. The only variance in the electrode placement can occur when the patient is supposed to undergo a continuous ECG, for example a 24h-monitoring, or is shaking. In this case the wrist and ankle electrodes may be placed on the shoulders, lower abdomen, thighs and forearms respectively to reduce the impact of body movement on the ECG. [7]

A 12-lead ECG uses ten electrodes. Six electrodes are placed on the chest and four usually on the ankles and wrists. Figure 2 shows each electrode position.

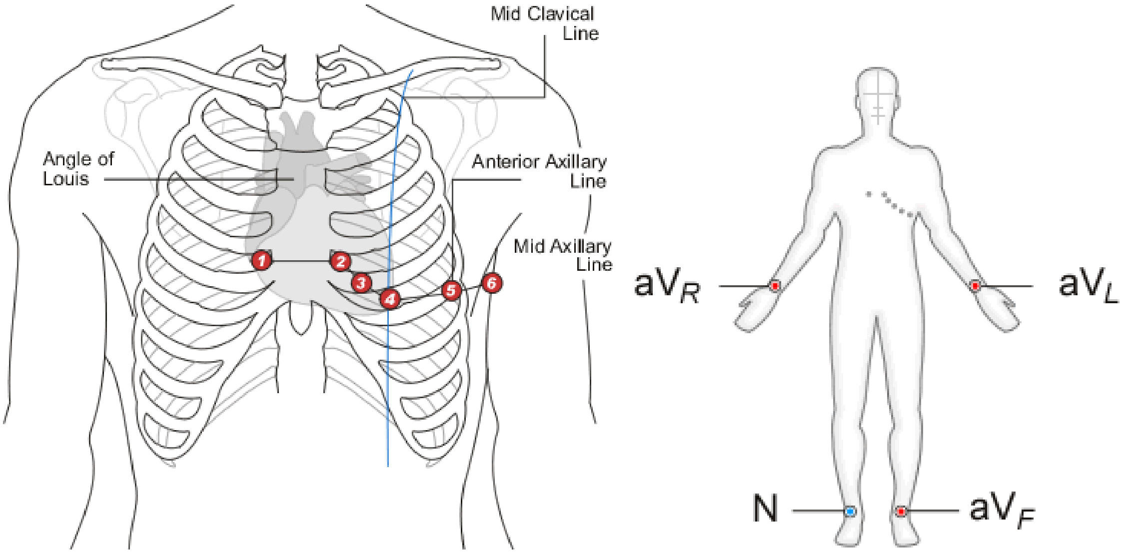


Figure 2. Electrode placement of a 12-lead ECG [8, 9]

The electrode on the right ankle, shown in figure 2, serves as a neutral connection in order to complete the electrical circuit of the measurement system. The remaining nine electrodes are used to measure 12 different electrical states of the heart, so-called leads. [9]

While the six chest electrodes V1 to V6 form unipolar leads and observe the electrical changes in their direct surroundings, the three limb electrodes form six leads from one electrode to another. These six leads are arranged in the so-called Einthoven’s Triangle as shown in figure 3. [8]

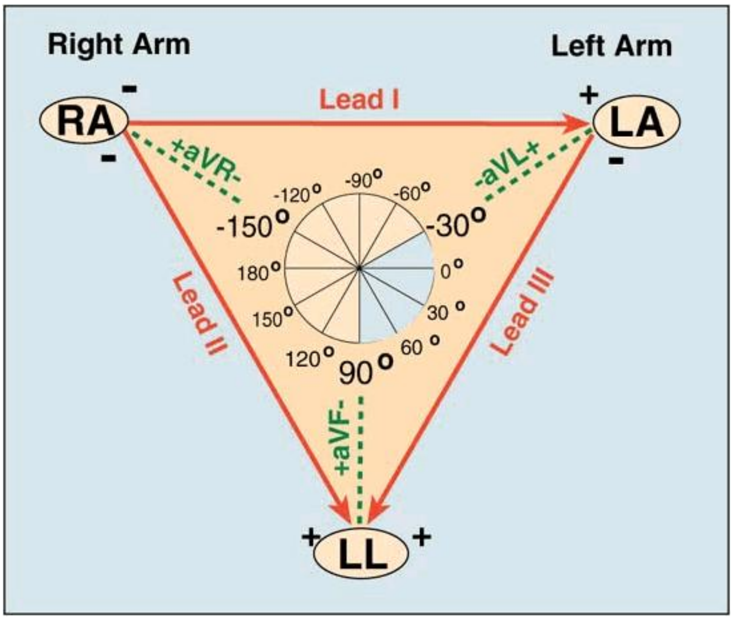


Figure 3. Einthoven’s Triangle [15]

Each of these leads has a certain polarity marked with the – and + symbols in the figure. In general, the leads I, aVR, and aVL are oriented from right to left and the leads aVF, II, and III go from the top to the bottom. [15]

Although the three limp electrodes may be positioned differently with each ECG measurement, they can always be assumed to form this triangle as depicted in figure 3. The three leads aVR, aVL, and aVF are so-called Augmented Vector unipolar leads and detect electrical changes with the line of sight indicated in figure 3. Similar, the bipolar leads I, II, and III detect electrical changes in their line of sight with the specialty that these leads are set between two electrodes, hence the name bipolar leads. [10, 11]

The twelve leads are displayed in a graph with three rows and four columns as pictured in figure 4. Usually in an ECG report, each lead is traced for 2.5 seconds.

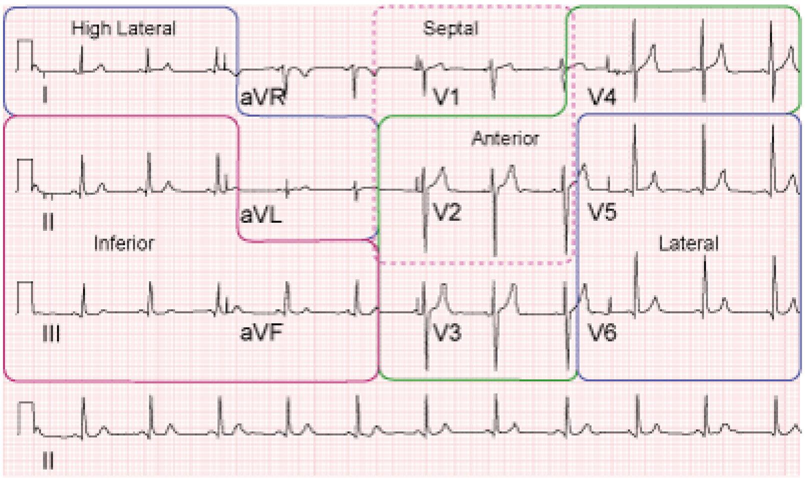


Figure 4. ECG report with highlighted regions of the heart [11]

Based on their position relative to the heart, the leads can be grouped together as highlighted in figure 4. For example, the leads aVL and II are positioned above the heart and therefore are named high lateral leads. Since the electricity usually travels from the top right to the bottom left through the heart, the position of each lead affects the direction the measured wave is pointing at. As an example, the leads aVR (right shoulder/wrist) and V6 (bottom left chest) detect the same waves pointing in opposite directions. [11, 12]

2.4.2 Sinus Rhythm and Polarisation Waves

An ECG is printed on paper with a special pattern of small squares with 1mm as side lengths. With the standard ECG paper speed of 25mm per second, the amplitude and time axes are scaled as shown in figure 5. [12]

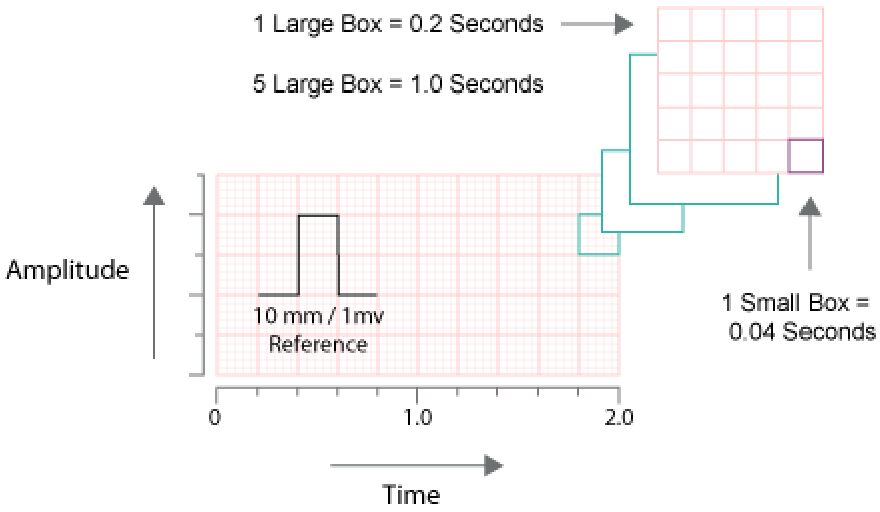


Figure 5. ECG paper with emphasised box dimensions [12]

A small box represents vertically 0.1mV and horizontally 0.04 seconds. In order to make reading the ECG easier, large boxes, each containing 25 small boxes, are drawn into the grid. These large boxes represent vertically 0.5mV and horizontally 0.2 seconds, so five large boxes horizontally are equal to one second and two large boxes vertically are equal to 1mV. [12]

Every heartbeat is visible as a characteristic pattern of waves. The normal rhythm of the heart is called sinus rhythm and consists of five, in rare cases six, waves with amplitudes of less than 5mV. A faster or slower pulse does not change the appearance of the sinus rhythm, but determines the distance between each repetition of the sinus rhythm. Figure 6 shows a sinus rhythm with the common five waves. [13]

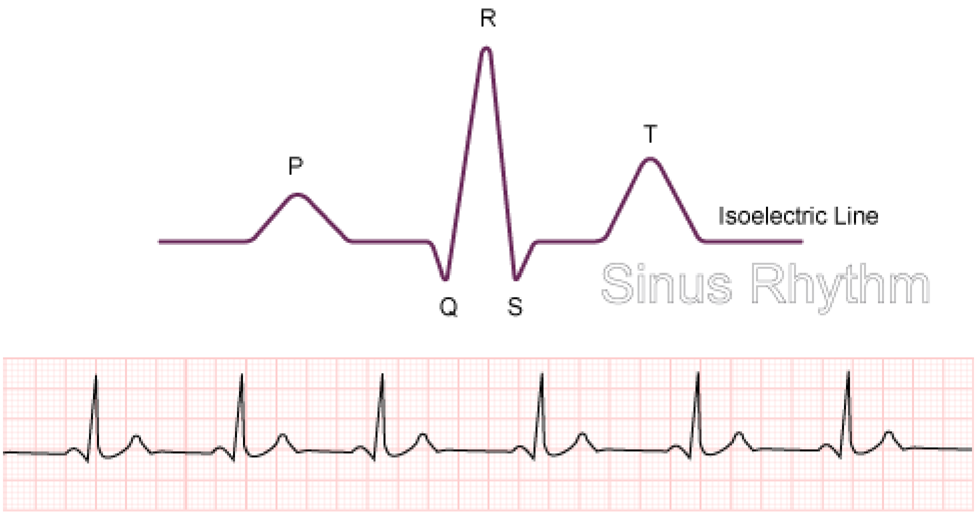


Figure 6. Sinus rhythm with five waves [13]

During the P wave, the atria are depolarised and release blood into the ventricles. As the atrial walls are relatively thin and the blood is sucked into the expanding ventricles, there is only a small amount of voltage necessary and therefore the P wave has a small amplitude. The QRS wave complex appears when the ventricles pump the blood out of the heart. They usually form a complex, since the Q and S waves are rather small, as illustrated in figure 6, and do not necessarily appear in an ECG report. The R wave is the biggest wave, because it appears when the ventricles depolarise, which requires the highest voltage compared to the electrical heart activity. The last wave represents the repolarisation of the ventricles and has a bigger amplitude than the P wave. [13 ff]

In some cases a small sixth wave can be seen after the T wave. This so-called U wave occurs with the repolarisation of the Purkinje fibres, a part of the heart’s stimulus transmission system. The ECG report can also show an amplitude in the place of a U wave caused by an electrolytic imbalance, but either way, an observable U wave is not very common. [14]

2.4.3 ECG Measurement System Setup

The requirements for the electrodes and the overall safety of the ECG device are similar to the ones applying to an EEG measurement system. Figure 7 shows a block diagram of a measurement system for a single ECG trace.

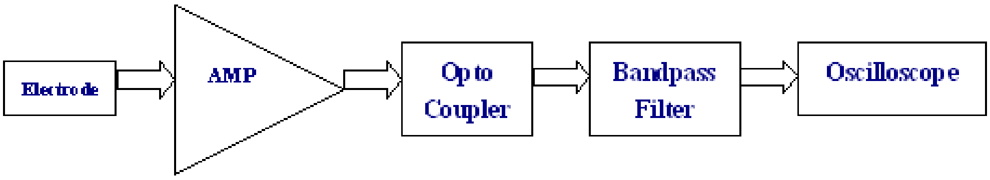


Figure 7. Block diagram of a single lead ECG measurement system [16]

Two electrodes are connected to the left and right chest and a third electrode on the right leg provides ground connection in order to complete the electrical circuit. The instrumentation amplifier is used to remove the common-mode component of the signal (i. e. a component of the signal that is not caused by the measured variable and is present on all conductors in the system) and to amplify the signal strength, so that small changes can be detected. For safety reasons the rest of the system is isolated from the body using an opto-coupler. [16]

In the next step, the signal is filtered with a bandpass filter, which removes those signal components lying in unwanted frequency spectra. These components can occur due to movement of the patient's body, electromagnetic interferences, or noise from other electronic devices. The bandwidth of interest lays between 0.67Hz and 40Hz for a standard ECG and between 300Hz and 1kHz for pacemaker detection. The final step is displaying the signal, for which in this setup an oscilloscope is used. [16, 17 p. 7]

The next section covers the material and devices which form the Metropolia Signals Box. The used hardware and software as well as the enclosure and the sensor connection are specified.

3 Material and Devices

This section provides an overview of the different material and devices to be used in this thesis. It covers both hardware as well as software.

3.1 OpenBCI Cyton Biosensing Board

The OpenBCI Cyton biosensing board shown in figure 8 is designed to measure ECG, EEG, and EMG parameters and transmit them wirelessly. It uses the RFduino radio module to communicate with every device compatible with Bluetooth Low Energy (BLE) or with a computer via the OpenBCI USB dongle. The Cyton board can be wirelessly programmed via this dongle as well. [18]

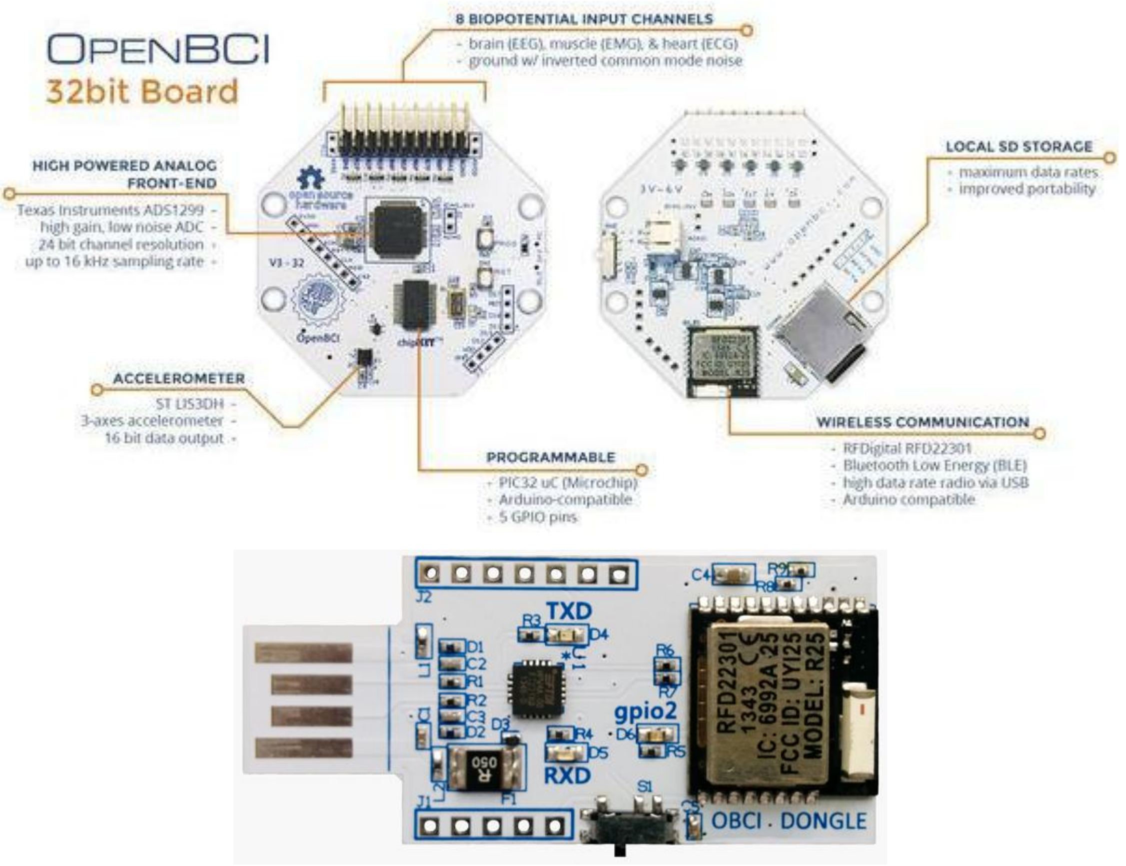


Figure 8. OpenBCI Cyton biosensing board and dongle [18, 20]

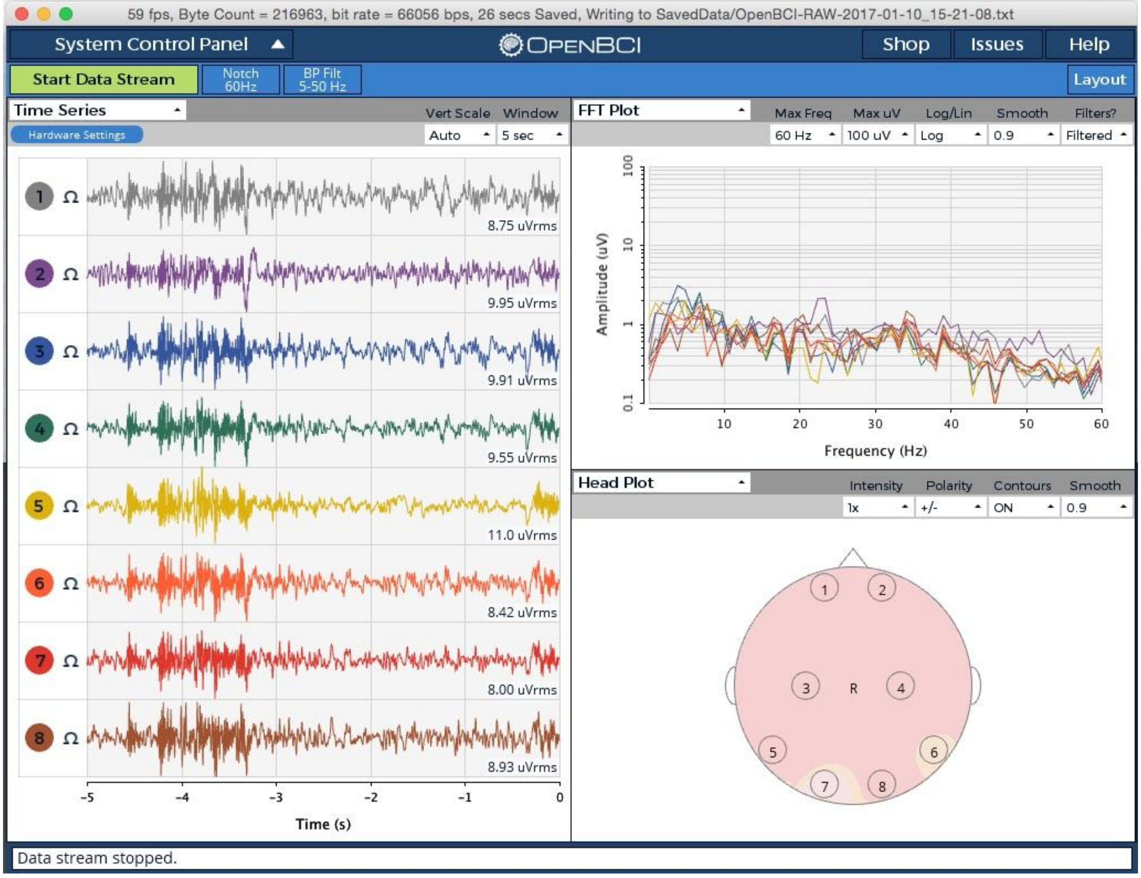
The Cyton board features the Arduino-compatible PIC32MX250F128B microcontroller by Microchip and digitalises analog signals via the Texas Instruments low-noise, 8-channel ADS1299 analog-to-digital converter (ADC) with programmable gain and 24-bit resolution. This ADC is designed with all necessary features for EEG and ECG measurements. A STMicroelectronics LIS3DH accelerometer and a micro SD card slot are included on the board as well. [18, 19]

The supplied 6V AA battery pack powers the board and the number of usable channels can optionally be increased from eight to 16 via the Daisy expansion module. OpenBCI offers several electrode kits as well as accessories such as conductive paste. However, every electrode that can be connected to the channel input pins can be used with this device. A graphical user interface (GUI) for working with this board is provided as well. Research will be carried out to which extent this software can be used in the scope of this thesis and what functions might need to be programmed additionally. [18]

3.2 OpenBCI Hub and Graphical User Interface

OpenBCI provides two software packets for working with their boards. The OpenBCI Hub serves as a connection between the dongle and the GUI. When using the board for a live session, it is necessary to start the Hub before the GUI. Other manipulation of the Hub is not necessary. However, for reviewing a stored session the Hub is not needed. [20]

With the OpenBCI GUI the user can easily process and view the data streamed from the Cyton board. The data is stored on a computer and optionally on a SD card attached to the board, which makes it possible to not only work with live data, but to review a stored session as well. Figure 9 shows the GUI after some example EEG data was received. [20]



59 fps, Byte Count = 216963, bit rate = 66056 bps, 26 secs Saved, Writing to SavedData/OpenBCI-RAW-2017-01-10_15-21-08.txt

Notch 60Hz

BP Filt 5-50 Hz

Time Series: Vert Scale Auto, Window 5 sec

FFT Plot: Max Freq 60 Hz, Max uV 100 uV, Log/Lin Log, Smooth 0.9, Filters? Filtered

Head Plot: Intensity 1x, Polarity +/-, Contours ON, Smooth 0.9

Data stream stopped.

Figure 9. OpenBCI Graphical User Interface [21]

The left side shows the signal sequence of each channel. On the right side a fast Fourier transform (FFT) plot of each signal as well as the electrode positioning on the head is displayed. This helps analysing the data further, for example brain waves can be determined by means of their corresponding frequency range. [20]

It is possible to set additional filters and to exclude individual channels from the data stream. Channels can be set to use their own reference voltage pin aside from the general reference voltage pin and the gain can be altered individually, too. A notch filter for 60Hz or 50Hz can be applied on the data as well in order to reduce the noise from the power supply of the computer. In figure 10 the filter options for each channel are displayed. [20]

	PGA Gain	Input Type	Bias	SRB2	SRB1	
1	x24	Normal	Don't Include	Off	No	0.00 uVrms
2	x24	Normal	Don't Include	Off	No	14.3 uVrms
3	x24	Normal	Don't Include	Off	No	0.00 uVrms
4	x8	Normal	Include	On	No	10.8 uVrms
5	x24	Normal	Don't Include	Off	No	0.00 uVrms
6	x24	Normal	Don't Include	Off	No	0.00 uVrms
7	x24	Normal	Include	On	No	14.4 uVrms
8	x24	Normal	Don't Include	Off	No	0.00 uVrms

Figure 10. OpenBCI Graphical User Interface Channel Settings [20]

In this setup, only the channels 2, 4, and 7 are used. To indicate this, the other channel numbers are gray. Channel 4 is used for EMG and ECG reading, so it uses a lesser gain than the channels 2 and 7, which measure EEG signals with a lower amplitude. Other settings not shown in figure 10 are excluding channel 4 from the Bias and SRB2 connection, since channel 4 uses its own reference voltage pin. [20]

The GUI provides a variety of additional functions (so-called widgets) besides the ones displayed in figure 9. For example, the user can see the accelerometer data or use a widget which utilizes the ADC connections of the microcontroller itself for measuring applied analog voltage. As the GUI is an open source software, it is possible to add own functions to the GUI or alter existing functions so they fit the needs better. [21]

3.3 LM35 Precision Centigrade Temperature Sensor

The LM35 sensor is a precise temperature sensor which provides an output voltage linearly proportional to the measured temperature in degree Celsius. In figure 11 such a sensor is displayed. [22]

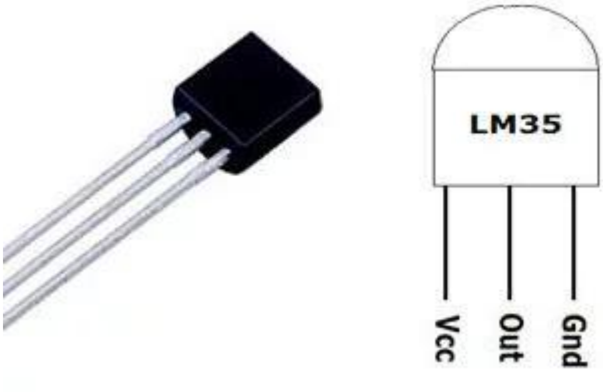


Figure 11. Texas Instruments LM35 Temperature Sensor and Pin Description [23]

Although the recommended supply voltage is between 4V and 30V, it is also possible to power this sensor with a voltage in the maximum range from -0.2V to 35V, which makes it possible to use the sensor with the 3.3V the Cyton board operates on. With drawing only 60µA from the power supply, the LM35 temperature sensor fits very well the needs of a battery powered device. The output voltage in a range from -1V to 6V represents directly the temperature in centigrade with a scale factor of 10mV/°C and it is not necessary to calibrate this sensor externally. The LM35 sensor tolerates temperatures from -55°C to 150°C and has an accuracy of ±¾°C over this temperature range. [22]

3.4 NTCLE100E3472JB0 NTC-Thermistor

A NTC thermistor is a resistor whose resistance decreases when the ambient temperature increases and is therefore suitable for measuring temperature. Figure 12 shows a NTC thermistor which is used in this thesis.

Figure 12. Vishay NTCLE100E3472JB0 NTC Thermistor [24]

This thermistor can be used in a temperature range from -40°C to 125°C and has a resistance of 4.7kΩ with a tolerance of ±5% at a reference temperature of 25°C. It can be used as part of a voltage divider powered by the Cyton board, so that the ADC function can still be used although technically the resistance needs to be measured. The datasheet provides a formula for converting the resistance of the NTC into the equivalent temperature. The next section shows how the materials described in this section are used to implement the required specifications of the Metropolia Signals Box. [24]

4 Results

This section starts with a comparison between the OpenBCI GUI and the specifications of the Metropolia Signals Box in order to determine which specifications are already covered by the GUI. Afterwards, two different approaches on how to implement the remaining specifications are described.

4.1 Comparison between OpenBCI GUI Functionalities and Specifications

Table 2 provides a recapitulation over the specifications of the Metropolia Signals Box. Additionally, it is marked whether the specification is covered by the GUI.

Table 2. Metropolia Signals Box's Specifications (Recapitulation)

Number	**Specification**	**Remark**
1	Non-invasive sensors (ECG, EMG, EOG, EEG, temperature, oximetry, pulse measurement)	Partially covered by GUI
2	Wireless transmission (Bluetooth or Wi-Fi)	Covered by GUI
3	Two hour storage on SD card (optional)	Covered by GUI
4	Wearability, easy to use	Covered by GUI

Table 2 points out that nearly all specifications are already covered by the OpenBCI GUI. The Cyton board itself is constructed to use Bluetooth for the wireless transmission. However, OpenBCI offers an optional WiFI Shield, therefore it is possible to cover both forms of wireless transmission named in specification 2 with the already existing software by OpenBCI. ECG, EMG, EOG, and EEG measurements are implemented in this software as well as the option for up to two hours of data storage on a SD card.

With powering the board via a battery pack and the overall littleness and light weight, the wearability of the setup is ensured. The use of the board and the software does not require much knowledge in biosignal measurement or hardware handling and besides the electrodes provided together with the board, an adapter to industry standard touch-proof electrode connectors is delivered with the board as well. This allows easy handling of the board and offers the possibility to use it with a huge variety of commonly used electrodes.

As provided by OpenBCI, the software does not include the possibility to measure temperature, oximetry or pulse. In the next step of this thesis it is examined how to include a temperature sensor as an example for adding features to the OpenBCI GUI. The remaining specifications were handled separately, because it is easier to include other additional sensors once the general way for doing so is figured out.

4.2 Serial Communication with the Cyton Board

Initially, it was decided to use another microcontroller board, the Cypress PSoC 1 evaluation kit, to gather and preprocess all relevant data for the remaining functionalities of the Metropolia Signals Box. These data should then be sent to the Cyton board via a serial connection, for example UART or I²C. This approach had the advantage that adding other sensors would be easily possible as long as the PSoC kit could send their data via the serial connection and that the PSoC kit is easy to configure and program.

On the Cyton side it only would be necessary to receive any data the PSoC kit sends and handle them together with the data the Cyton board itself gathers. Another advantage of this approach was that as the PSoC kit operates on 5V, sensors could be used which do not work with the 3.3V provided by the Cyton board. In order to maintain the required wearability, it would have been necessary to develop a way to power both boards with the battery pack

This approach seemed promising at first. But although the Cyton board has two UART serial ports, this approach could not be implemented, because one of these serial ports is reserved for the communication with the RFduino radio module and it was not possible to find more information on how to use the other one besides the information that it exists. Therefore the decision was made to include a temperature sensor directly to the Cyton board in order to examine the general possibility of extending its features.

4.3 Analog Voltage Read Widget

With the Analog Read Widget, three ADC channels can be used for measuring analog voltage. It uses the ADC integrated in the PIC32 microcontroller instead of the main ADC chip used for the eight biosignal channels. When using this widget, it is important to know that when the board is turned on, the ADC connection pins provide 3.3V until the Analog Read Widget is activated. It is recommendable to either integrate a protective circuit into the circuitry connected to the ADC or to establish the connection between ADC and sensor after activating the Analog Read Widget. This section explains further how this widget is used with the two temperature sensors.

4.3.1 LM35 as Measuring Device

The idea behind this approach is to use the PIC32 ADC for digitalizing the analog output voltage from the LM35 temperature sensor. The advantage of this sensor is that it is simple to convert the digitalized voltage value into the corresponding centigrade temperature. Since the temperature is scaled with a factor of 10mV/°C, the output voltage in millivolt is simply divided by ten to get the temperature. It is recommended to digitalize the output voltage in a way that the result represents the millivolt value in order to be able to measure the body temperature of a patient as precise as possible.

All necessary connection pins are included in the J3 header on the Cyton board. Figure 13 shows on the left how the LM35 sensor is connected to the Cyton board and on the right the setup in the laboratory.

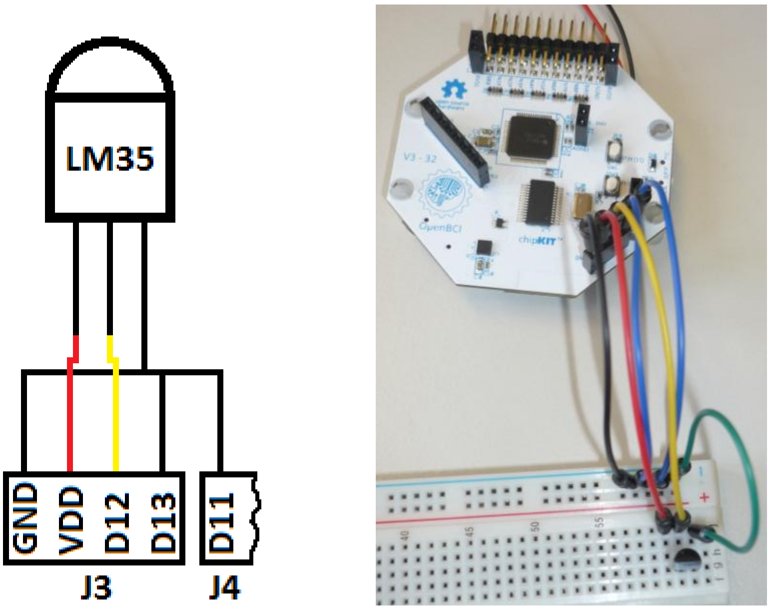


Figure 13. Schematic Diagram and Laboratory Setup for the LM35 [own figure]

The pins D11, D12, and D13 connect to the three ADC channels of the PIC32 microcontroller. Any of these pins can be used for the output signal of the LM35, pin

D12 was chosen, because it lies directly beside the supply voltage and ground connections. Connecting D11 and D13 to ground proved to stabilize the measured value on D12.

For implementing this approach, it is necessary to insert a few lines of code into the Analog Read Widget as shown below in listing 1:

```
//update the voltage values
val = hub.validAccelValues[auxValuesPosition];

//-----------------LM35-----------------------
val = (val*1.0008)-2.7277;     //compensate ADC value
val = (val*(3297.0/1024.0));  //val to mV
val = val/10.0;               //convert to temperature
//-----------------LM35-----------------------

analogValue.string = String.format(getFmt(val),val);
```

Listing 1. Converting the ADC value of the LM35 into the temperature

This listing starts in line 375 of the original Analog Read Widget. The code created for this thesis is placed between the line which fetches the ADC value from the OpenBCI Hub and the line which updates the graphical display in the GUI. *val* is a floating point variable and represents the current ADC value. For a more precise result the inaccuracy of the ADC is compensated using a formula derived from a best-fit line between the actual ADC value and the value an ideal ADC would have for a given range of input voltages. After that the ADC value is transformed into the corresponding analog voltage and divided by ten in order to convert it into the temperature.

In general, the temperature could be measured and displayed comparatively quickly, but there are some drawbacks in this approach. Since the PIC32 has a 10-bit ADC and the reference voltage is 3.3V, the voltage is digitalized with a resolution of about 3mV per bit. This means that without considering quantization errors the temperature can be measured with a maximal accuracy of 0.3°C, which is not as precise as necessary for medical purposes. Besides that, the reference voltage of the Cyton board fluctuates slightly in the range of 1mV to 3mV. While this does not affect the microcontroller, it changes the measured temperature value. An attempt was made to compensate this effect with the software, hence calculating with 3.297V instead of 3.3V, but it showed that for this compensation it would be necessary for the software to follow the fluctuation of the reference value.

While these drawbacks rendered it impossible to achieve a reading accurate enough for a body temperature measurement without adding a more complex circuitry for magnifying the considered voltage range the sensor provides in the temperature range of a patient, this approach is already useful in terms of observing the room temperature. For example, it could be investigated how a patient’s ECG reading is affected by the ambient temperature. As the task of this thesis includes measuring the body temperature, it is necessary to further improve the temperature measurement function. The next section shows a second approach using a different temperature sensor.

4.3.2 NTC Thermistor as Measuring Device

In this approach the NTC thermistor is used as one resistor of a voltage divider. Figure 14 shows the schematic and the laboratory setup.

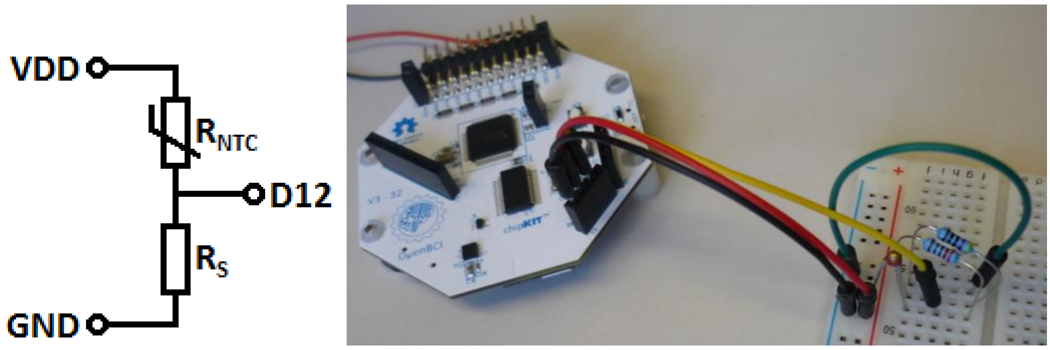


Figure 14. Schematic and Laboratory Setup for the NTC Thermistor [own figure]

The idea here is to measure the voltage U_S across the serial resistor R_S, use it to calculate the resistance of the NTC and then use the formula provided by the datasheet to calculate the temperature. Similar to the setup for the LM35 the voltage divider is connected to the J3 header of the Cyton board. The VDD and GND connections power the voltage divider and the ADC pin D12 is connected in a way to measure the voltage across R_S.

In order to achieve the maximal precision the resistance of the serial resistor should be as equal as possible to the resistance of the NTC at 37°C. This temperature was chosen, because it is the average body temperature of a human with good health. Using a formula from the datasheet, the resistance of the NTC at 37°C can be calculated with about 2.829kΩ. R_S is created with two standard resistors of 2.2kΩ and 470Ω. The resulting resistance of 2.67kΩ is as close as possible to 2.829kΩ using standard parts at hand.

In order to calculate the resistance of the NTC, the standard voltage divider formula for the voltage across R_S is rearranged:

$$R_{NTC} = \frac{VDD \cdot R_S}{U_S} - R_S \tag{1}$$

The formula for converting R_{NTC} into the corresponding temperature is provided in the datasheet:

$$T(R_{NTC}) = \left(A_1 + B_1 \cdot \ln\left(\frac{\mathrm{R_{NTC}}}{\mathrm{R_{ref}}}\right) + \mathrm{C}_1 \cdot \ln^2\left(\frac{\mathrm{R_{NTC}}}{\mathrm{R_{ref}}}\right) + \mathrm{D}_1 \cdot \ln^3\left(\frac{\mathrm{R_{NTC}}}{\mathrm{R_{ref}}}\right)\right)^{-1} \tag{2}$$

The parameters A_1, B_1, C_1, and D_1 depend on the material used in the NTC and are given in the datasheet. R_{ref} is the nominal resistance of the NTC at a given temperature, in this case the R_{25} value of 4.7kΩ. This formula provides the temperature in Kelvin, so in order to get the centigrade temperature, the result of the calculation needs to be subtracted by 273.15. Listing 2 shows the corresponding code in the Analog Read Widget:

```
//-----------------NTC-----------------------
for(int i=0; i<10; i++) {
    //update the voltage values
    val = hub.validAccelValues[auxValuesPosition];
    float userial = val*(3.3/1024.0); // voltage across Rs
    float rntc = ((3.3*2659.74)/userial)-2659.74; // get Rntc
    double   tempK   =   1/(0.003354016+0.000256985*log(rntc/4700.0)
                        +0.000002620131*log(rntc/4700.0)
                        *log(rntc/4700.0)+0.00000006383091
                        *log(rntc/4700.0)*log(rntc/4700.0)
                        *log(rntc/4700.0));  //Temperature in °K
    sum += (float) tempK-273.15;            // Temperature in °C
}
val = sum/10;
```

```
    //----------------NTC----------------------

    analogValue.string = String.format(getFmt(val),val);
```

Listing 2. Converting the ADC value of the NTC thermistor into the temperature

This code is placed below the same line in the Analog Read Widget as the code for the LM35 sensor. *val* and *sum* are again floating point variables and store the ADC value respectively the current sum for calculating the mean value of ten temperature values. This is done to stabilize the displayed value and implemented via a for-loop. *sum* is given the value 0 before each calculation of the mean value.

In order to further improve the measurement, the setup was soldered on a circuit board as displayed in figure 15.

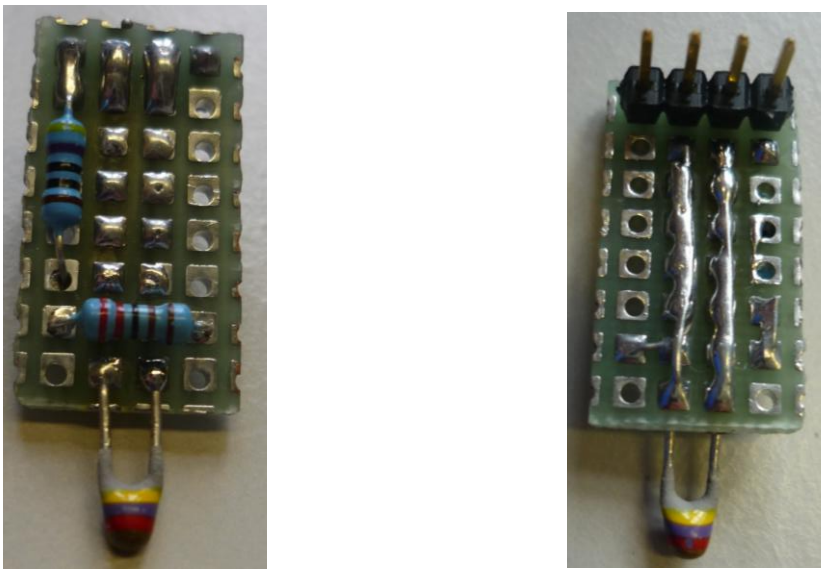


Figure 15. Soldered Circuit Board for the NTC Thermistor [own figure]

On the left the upper side of the circuit board with the two resistors forming R_S and the NTC thermistor can be seen. On the right is the lower side with the connections to the VDD and the D12 pins are displayed.

This approach worked out well. The temperature can be measured with an accuracy of 0.1°C and the display is stable. Since the voltage divider is powered with the reference voltage, this setup is immune to fluctuations of the reference voltage. Therefore it is possible to assume the reference voltage with 3.3V in the calculations above. Figure 16 shows the Analog Read Widget in the GUI.

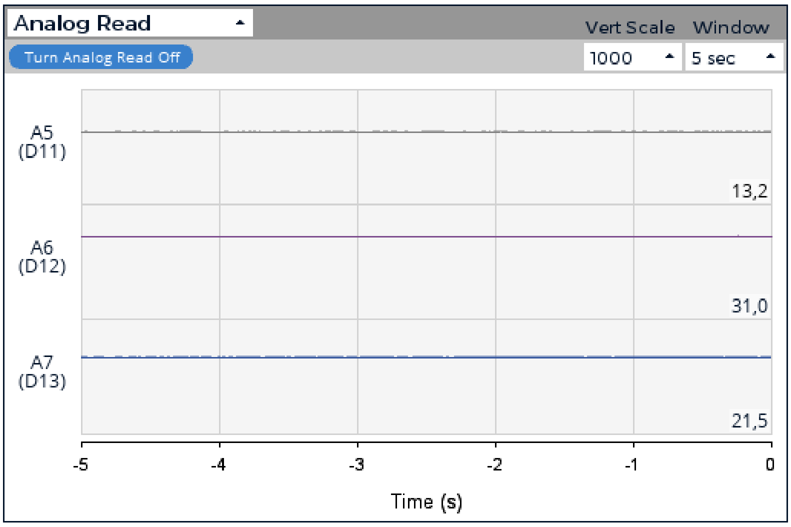


Figure 16. Analog Read Widget as displayed in the GUI [own figure]

As the pins D11 and D13 are not connected to a sensor, their values can be ignored. The D12 channel shows the measured temperature in degrees Celsius as a current value on the right and as a temporal course.

Additional improvements to the setup are using a more precise resistor with a resistance of 2.80046kΩ for R_S and including a cable connection between the NTC thermistor and the circuit board, so that the sensor can be attached to the patient's skin more easy. Figure 17 shows this improved circuit board.

Figure 17. Improved Circuit Board for the NTC Thermistor [own figure]

On the left the entire setup with the cable connection between the circuit board and the sensor can be seen. The right side shows a closer look on the circuit board. The bottom side of the circuit board is not shown, because all connections are made on the top side.

The power supply can be improved with using a power bank instead of standard batteries. In figure 18 the cable for connecting the board with a power bank can be seen.

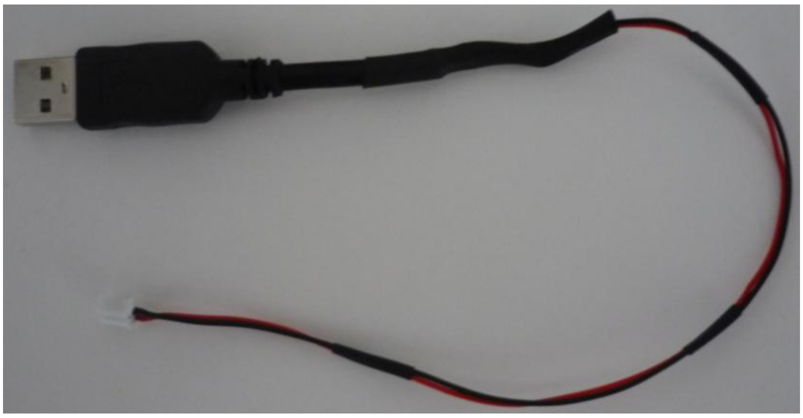


Figure 18. Connection Cable for the Use of a Power Bank [own figure]

This cable connects the power connection of a standard USB plug with a JST plug. Using a power bank instead of batteries provides a more stable supply voltage, which stabilizes the reference voltage of the ADC. The next section recapitulates over the process of this thesis and provides a conclusion of its results.

5 Conclusion

The main goal of this thesis was to develop a prototype for the Metropolia Signals Box. This Box should be able to measure several different biopotentials using non-invasive sensors, process those signals and store as well as wirelessly transmit them. It was one task to investigate to what extent the OpenBCI Cyton biosensing board could be used for this purpose. The second task was to extend the features of the board so that they meet the requirements of the Metropolia Signals Box.

It was found that this board and the software additionally provided by OpenBCI cover nearly all of the required features of the Metropolia Signals Box. However, there was still some work to be done to make the board meet all of the Box's required specifications. It was also possible to add a temperature measurement unit to the board. Understandably the main focus for digitalizing analog voltage is set on the biosignal channels, so the ADC of the microcontroller has a limited precision, but with some additional circuitry and the correct sensor type it was possible to measure the temperature precise enough for medical purposes. Still this ADC is already well implemented for temperature measurements with a precision of 1°C, so that without much external circuitry for example a room temperature can be measured.

The overall process of this thesis made clear that the OpenBCI board and software are great tools for working with several different biopotential measurements. The user does not have to have much experience in this field or understanding of hardware handling and first results can be easily achieved without the trouble of a big manual to be read first. Working with the source code is also easily possible, so the experienced developer can modify the existing software to his needs as well. This makes is easy to adapt existing functions to a different purpose.

References

1 Kortelainen O. *Metropolia Signal Box*. Helsinki, Finland: Metropolia University of Applied Sciences; 2017.

2 Johns Hopkins Medicine Health Library. *Electroencephalogram (EEG)*. https://www.hopkinsmedicine.org/healthlibrary/test_procedures/neurological/electroencephalogram_eeg_92,p07655
(accessed 26 February 2018).

3 Tatum WO, Husain A, Bembadis S, Kaplan PW. *Handbook of EEG Interpretation*. New York: Demos Medical Publishing; 2007.
https://ebookcentral.proquest.com/lib/metropolia-ebooks/reader.action?docID=317839
(accessed 26 February 2018).

4 Asanagi. *21 electrodes of International 10-20 system for EEG*. https://commons.wikimedia.org/wiki/File:21_electrodes_of_International_10-20_system_for_EEG.svg
(accessed 26 February 2018).

5 Teplan M. Fundamentals of EEG Measurement. *Measurement Science Review* 2002; 2(2): 1-11.
http://www.measurement.sk/2002/S2/Teplan.pdf
(accessed 26 February 2018).

6 Prutchi D, Norris M. *Design and Development of Medical Electronic Instrumentation: A Practical Perspective of the Design, Construction, and Test of Medical Devices*. Hoboken, New Jersey: John Wiley & Sons, Incorporated; 2005.
https://ebookcentral.proquest.com/lib/metropolia-ebooks/reader.action?docID=225809
(accessed 26 February 2018).

7 Moran G, Fecowycz A. *Cardiology Teaching Package – ECG Lead Placement*. https://www.nottingham.ac.uk/nursing/practice/resources/cardiology/function/placement_of_leads.php
(accessed 20 March 2018).

8 Moran G, Fecowycz A. *Cardiology Teaching Package – Chest Leads*. https://www.nottingham.ac.uk/nursing/practice/resources/cardiology/function/chest_leads.php
(accessed 20 March 2018).

9 Moran G, Fecowycz A. *Cardiology Teaching Package – Limb Leads*. https://www.nottingham.ac.uk/nursing/practice/resources/cardiology/function/limb_leads.php
(accessed 20 March 2018).

10 Moran G, Fecowycz A. *Cardiology Teaching Package – Unipolar Leads*.
https://www.nottingham.ac.uk/nursing/practice/resources/cardiology/function/unipolar_leads.php
(accessed 20 March 2018).

11 Moran G, Fecowycz A. *Cardiology Teaching Package – Bipolar Leads*.
https://www.nottingham.ac.uk/nursing/practice/resources/cardiology/function/bipolar_leads.php
(accessed 20 March 2018).

12 Moran G, Fecowycz A. *Cardiology Teaching Package – Role of the ECG Machine*.
https://www.nottingham.ac.uk/nursing/practice/resources/cardiology/function/role_of_ecg.php
(accessed 20 March 2018).

13 Moran G, Fecowycz A. *Cardiology Teaching Package – Sinus Rhythm*.
https://www.nottingham.ac.uk/nursing/practice/resources/cardiology/function/sinus_rythm.php
(accessed 20 March 2018).

14 Moran G, Fecowycz A. *Cardiology Teaching Package – The U Wave*.
https://www.nottingham.ac.uk/nursing/practice/resources/cardiology/function/u_wave.php
(accessed 20 March 2018).

15 Yanowitz FG. *ECG Learning Center – The Standard 12 Lead ECG*.
https://ecg.utah.edu/lesson/1
(accessed 20 March 2018).

16 Chen C-H, Pan S-G, Kinget P. *ECG Measurement System*.
http://www.cisl.columbia.edu/kinget_group/student_projects/ECG%20Report/E6001%20ECG%20final%20report.htm
(accessed 20 March 2018).

17 Paulus D, Meier T. *ECG-Amplifier*.
http://wwwmayr.informatik.tu-muenchen.de/konferenzen/MB-Jass2009/courses/1/Paulus.pdf
(accessed 20 March 2018).

18 OpenBCI Online Store. *Cyton Biosensing Board (8-channels)*.
https://shop.openbci.com/collections/frontpage/products/cyton-biosensing-board-8-channel?variant=38958638542
(accessed 19 March 2018).

19 Texas Instruments Incorporated. *ADS1299 Datasheet*.
http://www.ti.com/lit/ds/symlink/ads1299.pdf
(accessed 19 March 2018).

20 OpenBCI Documentation. *Cyton Getting Started Guide*.
http://docs.openbci.com/Tutorials/01-Cyton_Getting%20Started_Guide
(accessed 13 May 2018).

21 OpenBCI Documentation. *The OpenBCI GUI.*
http://docs.openbci.com/OpenBCI%20Software/01-OpenBCI_GUI
(accessed 13 May 2018).

22 Texas Instruments Incorporated. *LM35 Precision Centigrade Temperature Sensor Datasheet.*
http://www.ti.com/lit/ds/symlink/lm35.pdf
(accessed 14 May 2018).

23 Instructables – RudraNarayanG. *Measuring Temperature Using Sensor (LM35) and Atmega32.*
http://www.instructables.com/id/Measuring-Tempurature-Using-AVRATmega32-MCU/
(accessed 14 May 2018).

24 Vishay Intertechnology, Inc.. *NTCLE100E3472JB0 Datasheet.*
http://www.farnell.com/datasheets/2046167.pdf
(accessed 01 August 2018).