Master Thesis

Czech Technical University in Prague

F3

Faculty of Electrical Engineering
Department of Control Engineering

Electroencephalograph with high electrode density

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Field of study: Cybernetics and Robotics
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MASTER‘S THESIS ASSIGNMENT

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II. Master’s thesis details

Master’s thesis title in English:

Electroencephalograph with high electrode density

Master’s thesis title in Czech:

Elektrotencefalograf s vysokou hustotou elektrod

Guidelines:

Build an electroencephalograph with high electrode density
- Design and implement the electronics for EEG measurement capable of measuring 100 or more channels.
- Design and implement mechanical solution for positioning and wiring the individual electrodes.
- Implement firmware and software for the electroencephalograph control.

Bibliography / sources:

[1] Prutchi, D., Norris, M.: Design and Development of Medical Electronic Instrumentation: A Practical Perspective of the Design, Construction, and Test of Medical Devices. John Wiley & Sons, Inc. 2004.
[2] Xu, J., Mitra, S., Van Hoof, C., Yazicioglu, R.F., Makinwa, K.A.A.: Active Electrodes for Wearable EEG Acquisition: Review and Electronics Design Methodology. IEEE Reviews in Biomedical Engineering. 2017 ;10:187-198.

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III. Assignment receipt

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Date of assignment receipt Student’s signature

Acknowledgements

I thank the supervisor of this thesis for his help and guidance.
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Declaration

I declare that this work is all my own work and I have cited all sources I have used in the bibliography.

In Prague, 9. January 2024

Abstract

This work deals with designing and realizing an electroencephalograph (EEG). The design consists of measurement electronics of weak signals, a control board, communication with a computer, and a simple application to display and save measured data.

Keywords: electronics, EEG, low noise measurement, semi-dry electrodes, high-density electrodes

Supervisor: doc. Ing. Radoslav Bortel, Ph.D.

Abstrakt

Tato práce se zabývá návrhem a realizací elektrotencefalografu (EEG). Navrhuje se elektronika na měření slabých signálů mozku, řídící deska, komunikace s počítačem a jednoduchá aplikace pro zobrazení a uložení dat.

Klíčová slova: elektronika, EEG, nízkošumové měření, semi-dry elektrody, vysoká hustota elektrod

Překlad názvu: Elektrotencefalograf s vysokou hustotou elektrod

Contents

Chapter 1

Introduction

The brain is our most complicated and still not fully understood organ. It is responsible for processing our senses and makes us who we are. The interest in this organ has already begun in ancient Greece with the work of Alcmaeon.[tfece]

People have been looking for ways to explore the brain since ancient Greece, but much later, it was discovered that the brain emits weak electrical signals during its operation. Eventually, a German psychiatrist, Hans Berger, made a breakthrough and built a device later known as electroencephalograph, referred to as EEG, for an operation on his patient.[LK37] This amazing breakthrough will celebrate 100 years this year since it was built on July 6, 1924.

Doctors and researchers widely use the device to *diagnose and monitor a number of conditions affecting the brain.*[SERam] Therefore, the research and development continues making this device not only capable of better measurements but also more comfortable to the users.

To commemorate the anniversary and contribute to the ongoing research and the efforts of psychiatrists and neurologists, I will try to develop a new EEG device that would be cheaper than the commonly available ones but still ensure high-quality measurements. My main focus will be on the electrical part of the device.

I will provide a review of the state of the art of the current situation around EEG devices. The goals and requirements for the device will be stated according to the scan.

I will develop the whole device, not only by designing the theoretical circuit but also by selecting components, designing the PCB, and producing a prototype. I will aim to produce a device that can collect samples without a connection to a computer. Nevertheless, I will design electronics or add a way to connect it to a computer, too. However, programming required apps for computers/phones or even processing algorithms for EEG signals is out of the scope of this thesis.

Chapter 2

State of The Art

There are two primary types of EEG - portable/non-portable or using dry/wet electrodes. The resulting devices are always a combination of both.

Non-portable EEG must always be connected to a control unit that a measured person can not easily carry. Thus, the measurement must be performed in a limited space with limited maneuverability. Such an arrangement is suitable for routine examinations in the doctor's office but no longer for research and more complex examinations. Therefore, newly emerging devices are mostly fully portable.

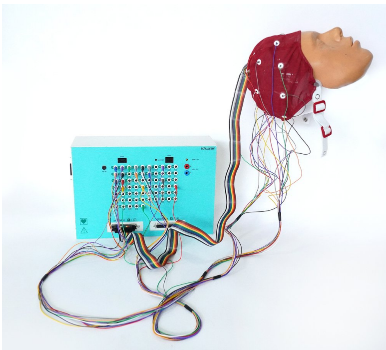

Figure 2.1: Example of old non-portable EEG[Chifa]

"Conventional EEG has been recorded with "wet" electrodes that use a layer of conductive gel or paste to increase conductivity between the electrodes and the test subject's skin. Applying gel can be time-consuming and may leave residue in the test subject's hair. Especially in studies that require high spatial resolution, with up to 128 or 256 electrodes, just setting up the experiment can take multiple hours per test subject. However, dry electrodes do not require conductive gel and are set up much faster. Without the use of a conductive substance, EEG signals can be noisier, and without the additional adhesion provided by the gel, they are more prone to motion artifacts. Therefore, dry electrodes are trading increased convenience for signal stability and quality."[R.ke] Moreover, dry electrodes are more suitable for extended wear because the liquid substance dries up over time. On the other hand, dry electrodes require pressure on the skin to maintain connection. That can bring discomfort and be painful after more extended wear. It seems impossible with the current state to have high-density dry electrodes, not only because of the pressure but also because just getting the hair and dead skin out of the way may be challenging in the case of 64 or more electrodes.

Figure 2.2: Example of dry electrode[KJ19]

Figure 2.3: Example of gel electrodes in a cap[Elees]

"EEG electrodes are produced with the shape of a cup, disc or needle, and are usually made of silver (Ag) and silver chloride (AgCl). Because Ag is a slightly soluble salt, AgCl quickly saturates and comes to equilibrium. Therefore, Ag is a good metal for metallic skin-surface electrodes."[AF65] Widely is also used gold (Au) usually in the form of coating. However, researchers are trying to use many different materials and shapes to improve their electrodes' abilities.

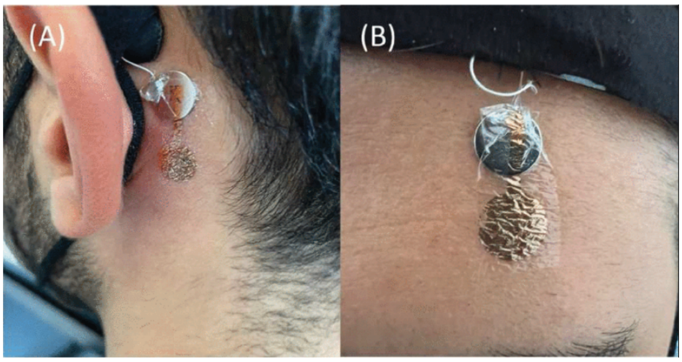

Figure 2.4: Example of a dry electrode using gold[CMS+22]

There is also a particular type of electrode called water electrodes. "Water electrodes, like dry electrodes, have a really short preparation time and do not require the use of a conductive gel. These electrodes can also be called 'semi-dry electrodes'. They can use sponges or some kind of mechanism to release the water continuously."[Elees]

The number of electrodes is very different for a given purpose and research. EEGs made for homemade use usually have lower numbers, from 4 to 12 electrodes, since their goal is to control movement on a computer for which they scan the cerebellum in the back of the brain.

Figure 2.5: EEG used for gaming[GRUgy]

EEGs used in laboratories can have any number of electrodes, usually in the range from 12 to 256, in order to be able to monitor the whole brain, as can be seen in the picture 2.3.

The price of electrodes with a cap vastly varies depending on the number of electrodes, type, and the materials used. One of the cheapest would be MindWave Mobile 2 from NeuroSky, which uses only one dry electrode (plus reference and grounding electrode). It is possible to buy it for less than $100. A more traditional version consisting of a cap with electrodes is possible to buy from $300 and more. For example, the cap with 128 gel electrodes in the picture below is possible to buy for $2500, and that is without any control unit that would process the signals from electrodes.

Figure 2.6: A commercially available model of a cap with electrodes[Ali7K]

The control unit has a purchase price in the order of tens of thousands of dollars depending on its capabilities, special features, and so on. The control unit from G.TEC Medical Engineering offers a unit called Main Amplifier Unit with 144 channels for $51 909. However, it can be used for measuring not only EEG but also ECG, EMG, and other body signals. Most control units offer a 1 kHz sampling rate, but this unit has a sampling rate of up to 38 400 Hz. There is also a difference in intention of usage. If it is intended for medical usage, it is more expensive. For example, the unit mentioned before costs $61 589 if it is intended as a medical device. The reason is the strictness of medical norms that must be upheld and certified.

Figure 2.7: An amplifier unit from g.tec[g.tmp]

Chapter 3

Defining Requirements for EEG Device

It was decided to build an electroencephalogram using semi-dry electrodes based on the previous chapter. They use salinated water to increase conductivity, so the design is not so demanding for dealing with problems of dry electrodes. Since the conductive substance is water, it is more comfortable than traditional gel. These electrodes require much less effort to properly install on a patient compared to the one using gel.

The desired number of electrodes is 128[1] since that amount can cover most of the brain pretty densely, and it should be sufficient for most of any additional research that would use the newly developed device.

Bringing measurement electronics as close to the electrodes as possible would reduce problems with long cables and requirements for noise resistance. Therefore, Small EEG cells will be created. Each of them will have connected eight electrodes and will be doing the measurement and conversion from analog to digital. These cells will allow to have a small amount of cables leaving a cap with electrodes, which will significantly contribute to the comfort of not only the operator but also the patient. Of course, it will bring some disadvantages, like the need for communication with several boards that includes more management in communication, timing, and other problems. The most significant disadvantage is the need to protect the electronics against water that could damage them.

Lastly, A control board will be created that can manage all the communication. It will command the cells, read data from all cells, and send data via WIFI to another device like a computer or others, capable of communicating with a TCP server.

Such an amount of electrodes and usage of water is not suitable for extended measurement. The device will be wearable and sufficiently small so the patient can easily move and does not have to sit or lie. That will make this

[1]The device will be capable of using 128 electrodes, but 127 electrodes will be used on a cap due to the required symmetricity.

device usable for broader applications for researchers or doctors. To fulfill such a purpose, a battery will be added. But at the same time, There will be a possibility of supplying the device from the power grid and charging the battery through it. The battery will also provide a backup supply in case of a blackout.

The cap and electrodes are provided by the department. Therefore, this thesis will not provide many details about them.

Chapter 4

EEG cell

The measurement equipment must be suitable for voltage levels and frequencies for EEG. "The amplitude of the EEG is in tens of microvolts when measured on the scalp, and about 1-2 mV when measured on the surface of the brain. The bandwidth of this signal is from under 1 Hz to about 50 Hz, but that depends on the wanted signal."[JR95] For example, the Gamma frequency activity can go up to 150 Hz. Any noise for such small voltage levels will have a fatal effect on the measurements. It will have to be amplified quite a lot, so saturation of the amplifier will become a problem, too.

4.1 Prototype

It may prove challenging and expensive to try creating this measurement part into the final piece right away. Therefore, creating a prototype where it is possible to test different components and styles of routing, but also communication may eventually save time, money, and much work.

I propose making the measurements with the circuit in the image below based on the abovementioned requirements.

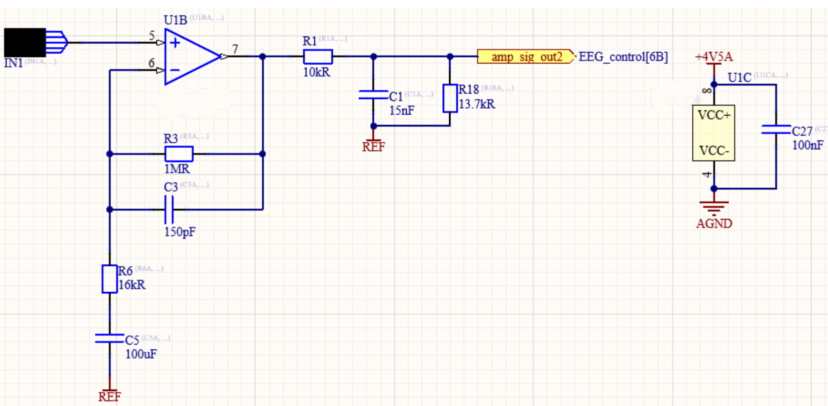

Figure 4.1: Proposed amplifier circuit

The circuit contains

- a measuring electrode (IN1),
- an amplifier in a non-inverting circuit,
- an RC filter of the first order and
- a voltage divider to adjust the output voltage.

The gain of the amplifier was chosen by the formula 4.1. Wanted gain is around 60 based on available resistors. The resulting gain is 63.5.

$$Gain = 1 + \frac{R3}{R6} \tag{4.1}$$

Two candidates for the amplifier were chosen. One of them has lower noise, better common mode rejection, and more but requires at least a 4.5V supply, and the upper input voltage is extremely limited to (V+)-3.5, where V+ is the voltage on a positive power rail of the amplifier. The other one has slightly worse parameters but can work with as little as 2 volts.

The C5 capacitor's purpose is to extract DC bias and thus connect only alternating signal so just the alternating signal would be amplified.

C3 is part of a low-pass and anti-aliasing filter. R1 and C1 create a low-pass filter, and R1 and R18 will act as a voltage divider to protect the input of ADC against higher voltage. The value of R18 must satisfy this equation:

$$3.3 - REF >= (4.5 - REF)\frac{R18}{R18 + R1} \tag{4.2}$$

The equation expresses that the residual positive range of ADC on the left side must be greater or equal to the voltage after division. (3.3 V is the supply voltage of ADC, and 4.5 V is the supply voltage of amplifiers)

Capacitor C27 acts as a blocking capacitor to filter the amplifier's power supply.

Having just the currently used filters with passive components, as seen in the figure 4.1, may not be enough to filter out the noise sufficiently. However, the output of the amplifier that passes the low-pass filter (R1 and C1) and voltage divider (R1 and R18) continues to a sigma-delta ADC where the signal is further filtered by exploiting the principle of sigma-delta ADC. An ADC component with a truly independent 8-channel sigma-delta ADC was chosen.

To ensure the supply voltage for amplifiers and ADC is as smooth as possible, the board gets a 5V power supply for the analog part and 3.3V for the digital part. Two low-dropout voltage regulators (LDOs) stabilize 5V to 4.5V and 3.3V. The ground is also separated into analog and digital parts. (The grounds are connected to each other but only at one point, and that point is on the main board. For more info, refer to chapter 5). Since there will not be much space, TPS7A2045PDQNR and TPS7A2033PDQNR were chosen for this job in the X2SON package. The advantage of these LDOs is their tiny size, very low dropout and inrush current, and their ability to deliver up to 300 mA.

In order to sample measurements simultaneously, the main board distributes a clock used for sampling and communication. It is distributed using Low Voltage Differential Signaling (LVDS). The communication uses the Universal Synchronous Receiver/Transmitter (USART) protocol. More about LVDS, wiring, and messages can be found in chapter 5. LVDS receiver for a clock is SN65MLVD3DRBT, and the receiver/transmitter for communication is SN65MLVD204BRUMR.

One last feature was added - a way to detect poorly connected electrodes.

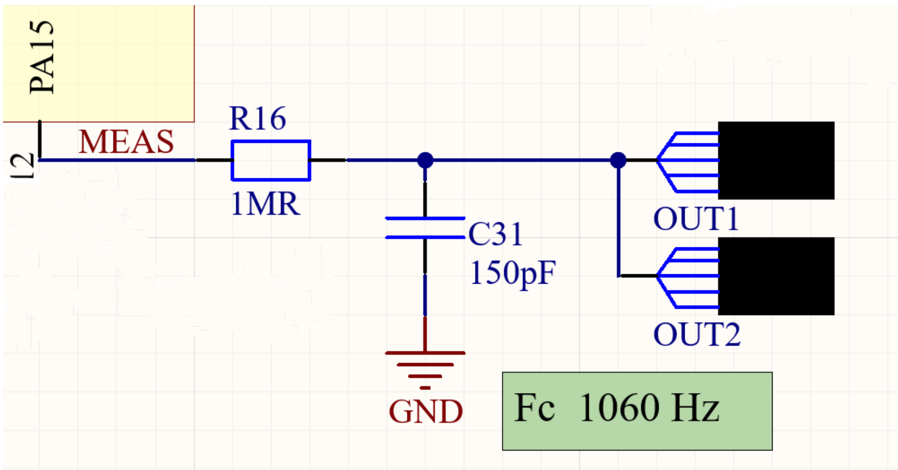

Figure 4.2: Circuit to detect badly connected electrode

1 kHz PWM signal generated by the processor passes through an RC filter with a cut-off frequency at cca 1060 Hz, which filters it and creates a "steady" voltage level dependent on the duty cycle of the PWM signal. Controlling the duty cycle makes it possible to create a sinus-like signal. For example, by a technique called "Angle Step Rate"[U.al].

The idea behind this signal takes into account the parasitic coupling between this sine-like signal and the signal measured on electrodes. The hypothesis is that the 1 kHz signal will be more visible from a poorly connected/attached electrode rather than a good one. Different styles in the routing of the trace carrying sine-like signal were set in place to compare differences and pick the most suitable one.

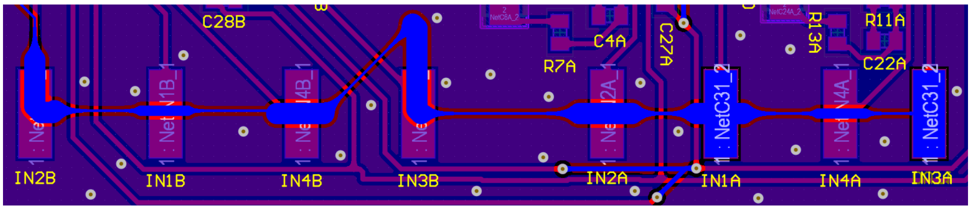

Figure 4.3: Different styles in routing (blue trace) under electrode's connection

Routing styles come in pairs to be tested with different amplifiers, too.

Lastly, an amplifier as a voltage follower was added to the incoming REF signal to vastly reduce current and increase stability.

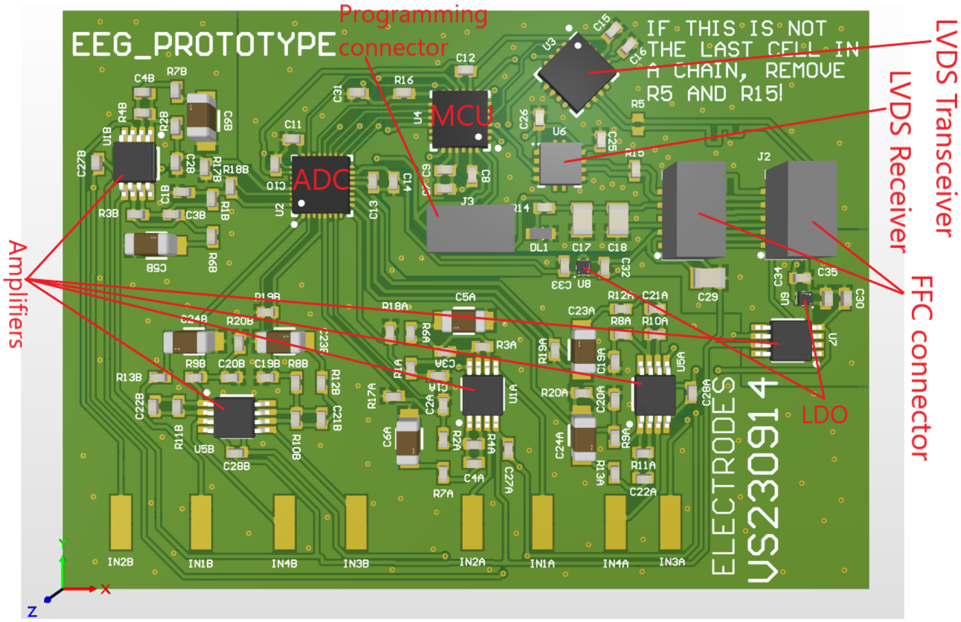

Figure 4.4: Prototype of EEG cell PCB

4.2 Pilot Version

It was concluded that the original idea of measuring and acquisition of EEG signals is viable after intensive testing and measuring. However, a few changes have to be made.

- Size and shape
- Change of connectors
- Big capacitor
- Reference voltage level
- Circuit for detection of poorly connected electrodes

The original **FFC connector** relied solely on the friction, but that did not hold the cable tight enough, and in case of unplugging, dramatically damaged the cable, which is not practical, especially for the testing and development phase. Therefore, the connector was changed for a model that has an active lock - FH12-10S-0.5SVA(54)

The measurement circuit must have been slightly changed. See this picture and compare it with picture 4.1.

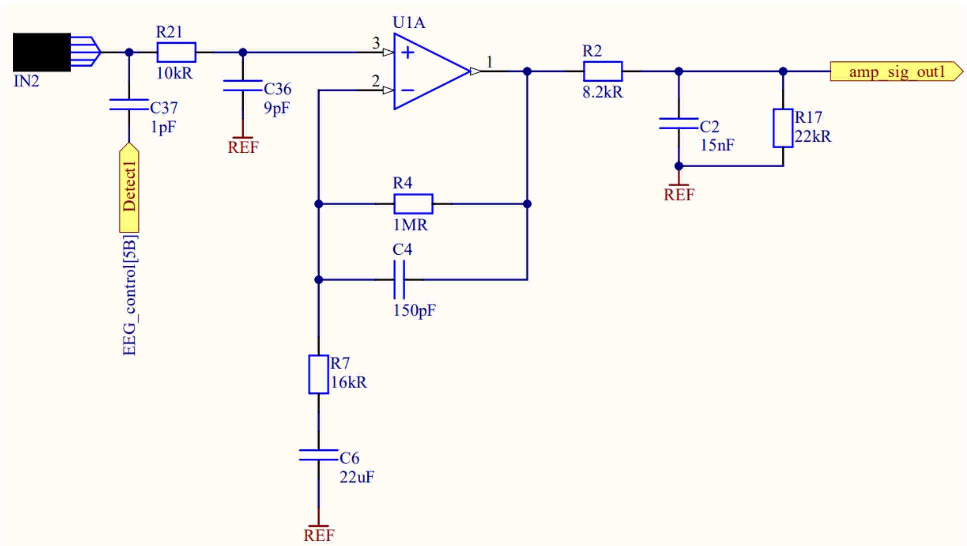

Figure 4.5: Measuring circuit in pilot version

There are three changes: on the positive input of the amplifier, the size of capacitor C6, and the values of resistors on the output.

Chosen amplifier have a limitation on the input voltage, limiting it quite a lot. Therefore, the reference signal had to be reduced to 0.5V. This change required changing the output divider resistors to 8.2kΩ and 22kΩ since the original expected reference signal value was around 1.8 to 2.2 V.

Originally chosen capacitor - 100 μF in size 0805 had a dielectric X5R. It turned out to be too temperature unstable, and a small change in temperature due to normal operation or just a small gust of wind was visibly adding unwanted noise. Unfortunately, there was none with a dielectric that would offer better temperature stability in this size, and due to size restrictions, it was not possible to choose a larger capacitor. Therefore, the only option was to shrink the value. It allows to have a capacitor with X7R dielectric that offers better temperature stability. That proved to be enough for this purpose. A lower value shifts the filter closer to the desired frequency border - 0.5 Hz, whereby the gain on that frequency is lower. It is not too dramatic a change.

The voltage on the input of the amplifier (V_{in}) relative to the reference (REF signal - used 0.5 V) can be computed using this formula:

$$V_{in} = \frac{\frac{REF_{ADC}}{2^{23}} \times OUT \times \frac{R2+R17}{R17}}{GAIN}, \tag{4.3}$$

$$V_{in} = \frac{\frac{1.2}{2^{23}} \times OUT \times \frac{30.2}{22}}{63.5}[V]. \tag{4.4}$$

Where REF_{ADC} is an internal reference of ADC, OUT is a digital output of ADC ($\pm 2^{23}$), and $GAIN$ is the gain of created non-inverting circuit (See the equation 4.1).

The R21 and C36 allow putting an RC filter on the input of the amplifier to suppress the high-frequency interference.

There is also one picofarad capacitor on the input that connects one end to the output of the RC filter in the picture 4.2 that creates the sine wave to detect poorly connected electrodes. The prototype relied on parasitic coupling, but that is not reliable enough. It was changed to connect it directly through a small capacitor.

That reliably puts the sine wave into the signal on the electrode. The signal induced by this wave has an amplitude of 6 mV, as seen in the picture from an oscilloscope on the next page.

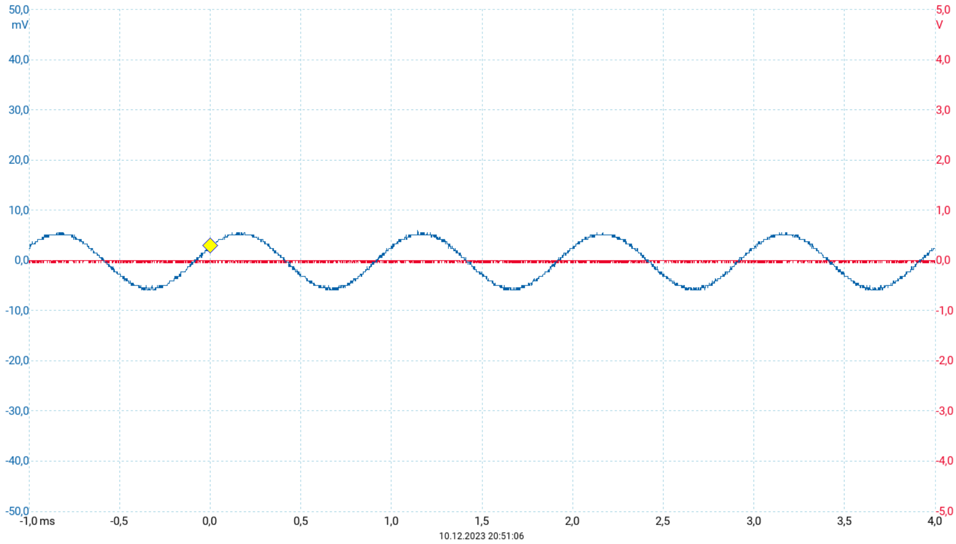

Figure 4.6: The signal on an unconnected electrode

The last change from the prototype is its shape and size. The intended place for the cells is on the head among the electrodes, but the space is limited due to the large number of electrodes.

The board will have a circle shape with a hole in the center where one electrode will be placed. Since the electrodes have two centimeters between each other's centers and the diameter of an electrode is 1 cm, the radius of the board for cells cannot be larger than 15 mm, and the hole in the board must have a radius of at least 5 mm. Tremendous effort was put towards shrinking the board, and eventually, a 14.5 mm radius of the board and a 5.5 mm radius of the hole in the center were achieved. That makes the cell area only 21,92 % of the prototype's area. That is less than one-fifth of the original size.

To reduce it so much, the board must have at least 4-layers to allow routing in such limited space. Also, some components had to be placed on the opposite side, especially the connectors.

4.2.1 3D View

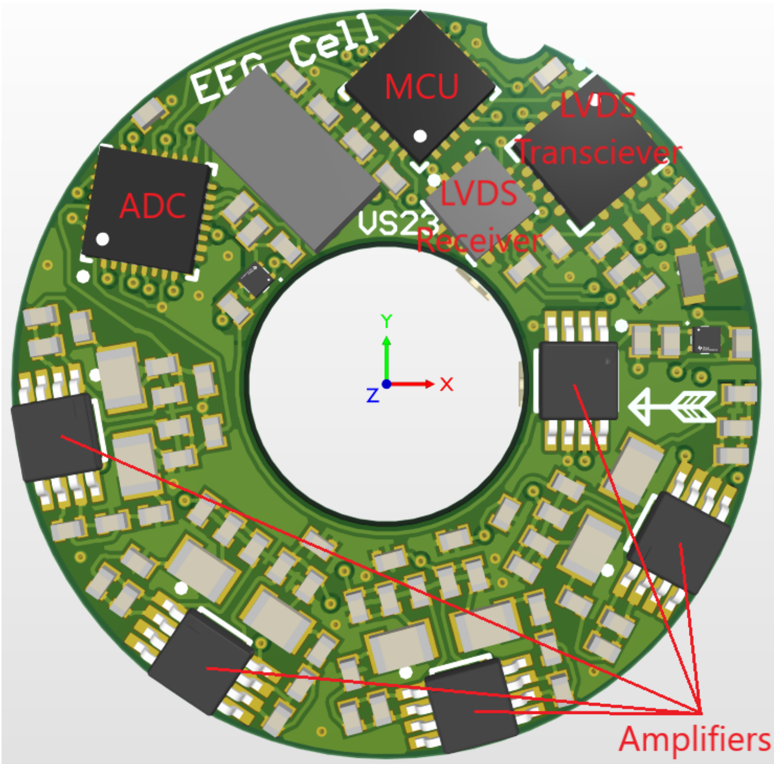

Figure 4.7: Pilot version of cell - Top View

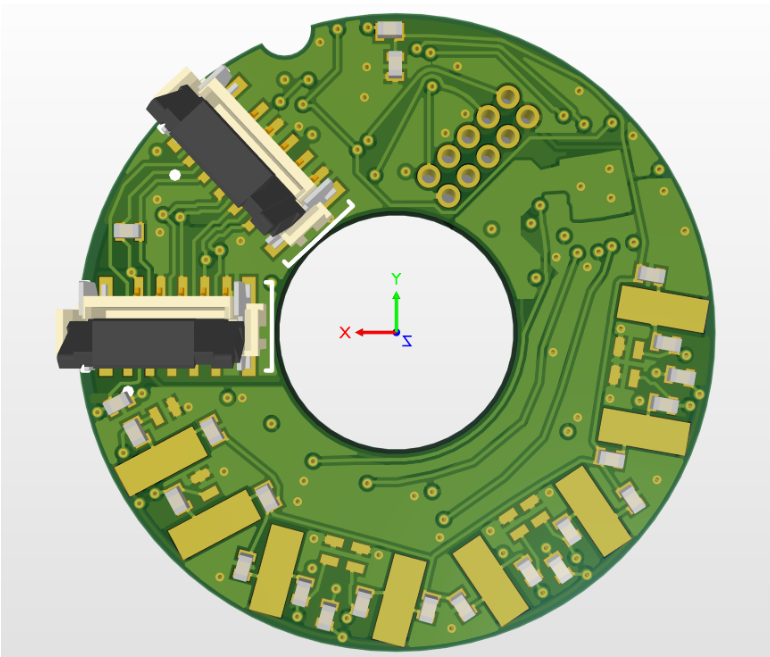

Figure 4.8: Pilot version of cell - Bottom View

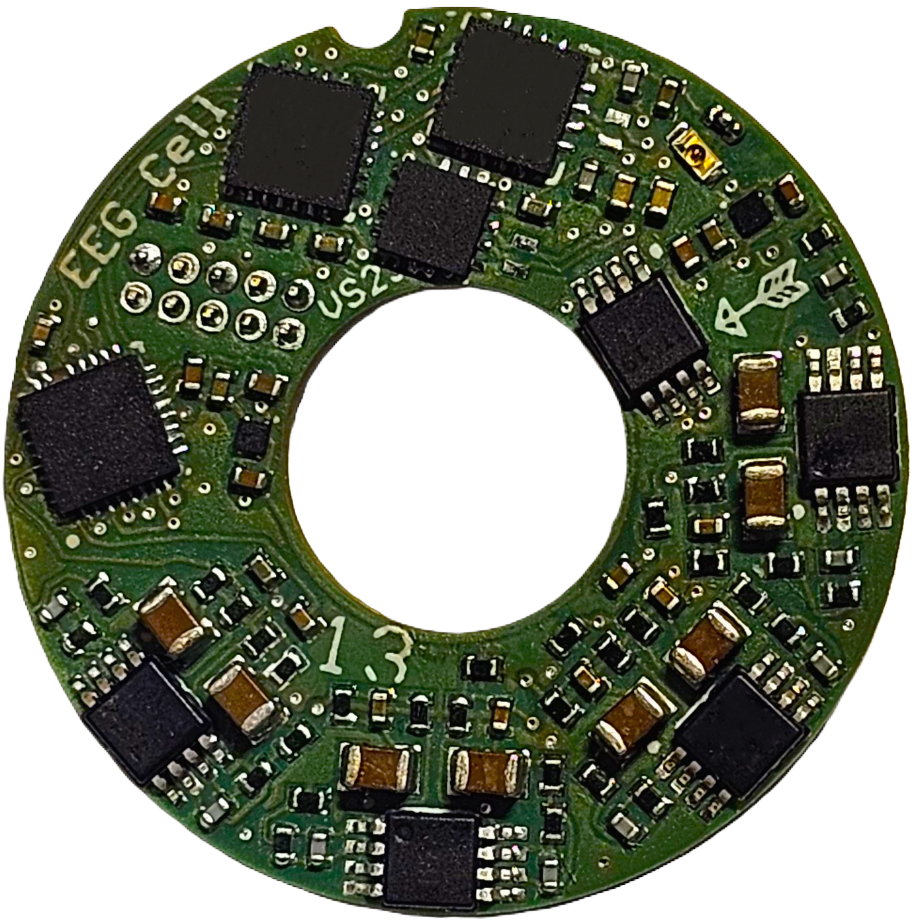

Figure 4.9: Pilot version of cell - realization

Chapter 5

Main Board

The second part of the EEG device is the main board. The requirements for this board are:

- Control communication with all cells - commands and receiving data
- Distribute power
- Use of a battery to be wearable
- Create and distribute clock
- Creating reference signal and connection of a reference electrode
- Sending measured data via Wifi for further processing

MEMS oscillator creates a clock with a frequency of 8.192 MHz. This frequency was chosen since the ADC on Cells requests it for high-resolution mode. The clock is distributed to Cells and is used as an external clock for MCU and USART.

5.1 Communication with cells

5.1.1 Hardware

The communication with cells is through LVDS using half duplex USART protocol as mentioned in Chapter 4.1. The board uses a 4-channel transceiver. Therefore, all cells will be divided into four groups, each with its independent channel. This arrangement increases the amount of data that can be delivered.

Multidrop configuration is used for distributing the clock. A single driver with multiple receivers is used in this configuration. The transmission line is terminated only at the end (on the last Cell in a chain) by a termination resistor.[M.2F] The value of the resistor is not known beforehand since it depends on used cables and connectors, but the universal choice is 100Ω and usually works pretty well.

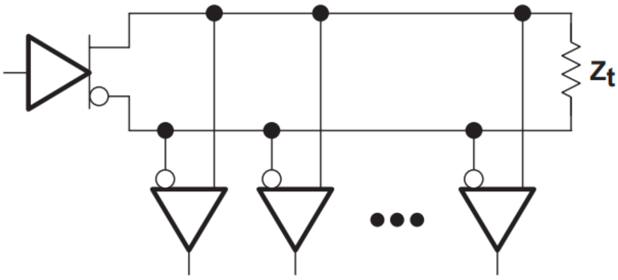

Figure 5.1: Multidrop configuration [M.2F]

Multipoint configuration is used for data transmission. The configuration contains many drivers and receivers since transmitting and receiving are required for data communication. The double termination is needed; therefore, there is a termination resistor not only at the end but also at the beginning (on the main board).[M.2F] The value for these resistors is the same as for the previous configuration.

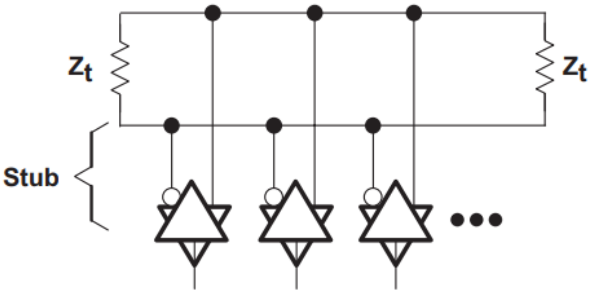

Figure 5.2: Multipoint configuration [M.2F]

5.1.2 Communication principle

The Main Board, the host of this communication, expects four cells on each channel with assigned addresses - from 0 to 3 on the first channel, from 4 to 7 on the second channel, and so on.

Initialization and timing can be seen in the following picture. The main board takes control of communication, sets the line to a high level in less than 1 ms after the power-up, and transmits the first synchronization message after 20 ms. The cells start to listen approximately in the middle of the interval to ensure that the state on the line is well-defined.

Cells reset ADCs on the first synchronization message to synchronize them. They start transmitting data after the next sync message in their order on the channel - the lower number sends data sooner.

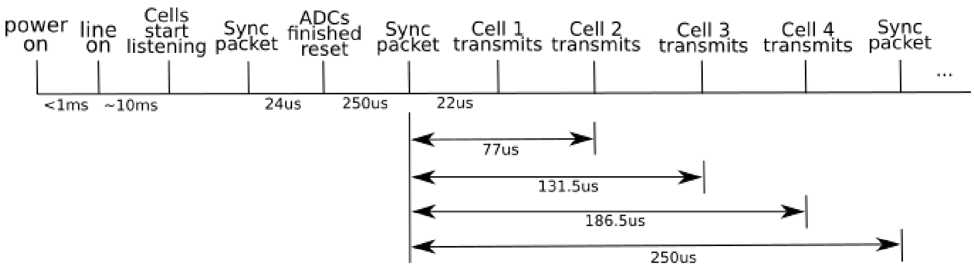

Figure 5.3: Start-up of communication via USART

The time between the start of transmission of individual cells is around 55 us. They first set the line to a high level for 8.6 us to give the main board enough time to turn on DMAs and listen on all channels, which takes around seven microseconds. Transmission of all bytes from one cell takes 33.5 us, and there is a small reserve at the end of transmission before the cell gives up on control of the line. The detail of communication from osciloskop is on the following graph, where the rise of the red line marks the start of the preparation of DMAs and turning on the listening at individual channels. The falling edge marks the finish of preparations. The blue line is a positive line of the differential line LVDS.

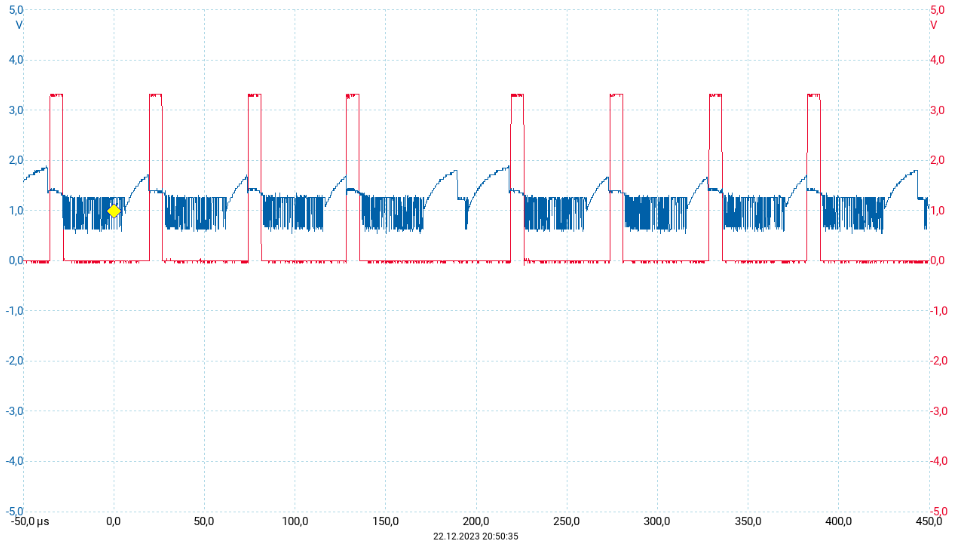

Figure 5.4: Record of communication via an oscilloscope

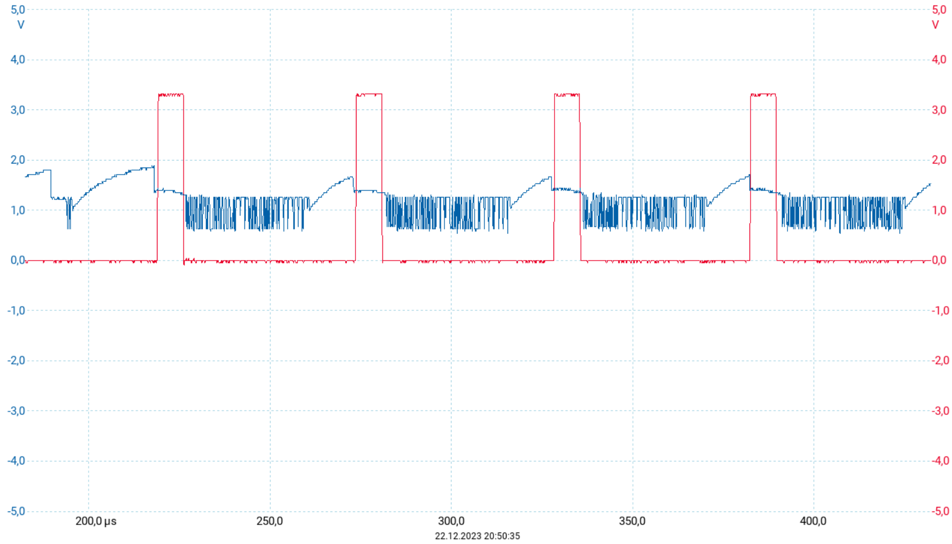

Figure 5.5: Detail of one sequence

The host sends these messages simultaneously on each channel and handles them independently.

Messages format

The host sends one byte only in the predefined time slots since the cells listen only during that time. The host can choose from these messages:

- **0xAA** - message for synchronization - let the cells know when they are supposed to start sending the data
- **0xAC** - has the same function as the previous one but also tells the cells to start a 1 kHz sin wave to detect poorly connected electrodes. The wave will be output for 10 seconds.

The answer from a cell is:

- one byte as a header - **0xAY**, where Y is the address of a cell (from 0 to 15).
- followed by 24 bytes of measurements from ADC - 3 bytes for each channel. To convert it into 32-bit integers, it must be MSB's sign extended.

5.2 Power Supply

There are three ways to power the main board:

- Battery (Single cell)
- Via USB-C
- Via Dual DC Socket - 2.1 mm or 2.5 mm plugs

The advantage of this solution is its possibility of using all three ways simultaneously or just one. The device decides which source it will use. Having a battery and at least one of the other power supply options will result in charging the battery. The device will take care of this process and safely charge the battery. It ensures to charge it appropriately and not to heat it up too much.

Chosen connectors allow a wide variety of adapters, but special care must be taken in choosing one. **Only medical adapters** can be used with this device since there is not enough protection for the patient/operator to use it with a regular one. An example of a suitable adapter could be GSM60B05-P1J.

The battery can have up to 4.4V, and the adaptors connected to USB-C[1] or Dual DC Socket can have up to 17V.

5.2.1 Circuits of Power Supply

USB-C connector for power is wired as USB 2.0, which requires a 5.1 $k\Omega$ resistor to each CCx pin. Data pins are not connected anywhere.

Power from the USB-C connector (in image 5.6 marked as VCC2) continues to a multiplexer together with power from the other connector (VCC1).

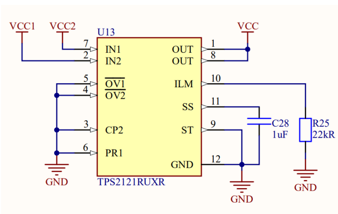

Figure 5.6: Wiring of power multiplexer

[1]There are two on the board, but only one is intended for delivering power since the other is used only for testing as USB. Both connectors have labels (POWER, USB) next to each other to distinguish them easily.

The multiplexer also serves as a current limiter and ESD protection. The value of resistor R25 sets the limit for the incoming current.

Next component must take in voltage from the battery and the chosen power supply from the multiplexer and adjust the voltage for the rest of the system. Therefore, the next component is an adapter charger with power management. The component U7 (see image 5.7) controls how much current goes to the battery and the system depending on the system's power requirements.

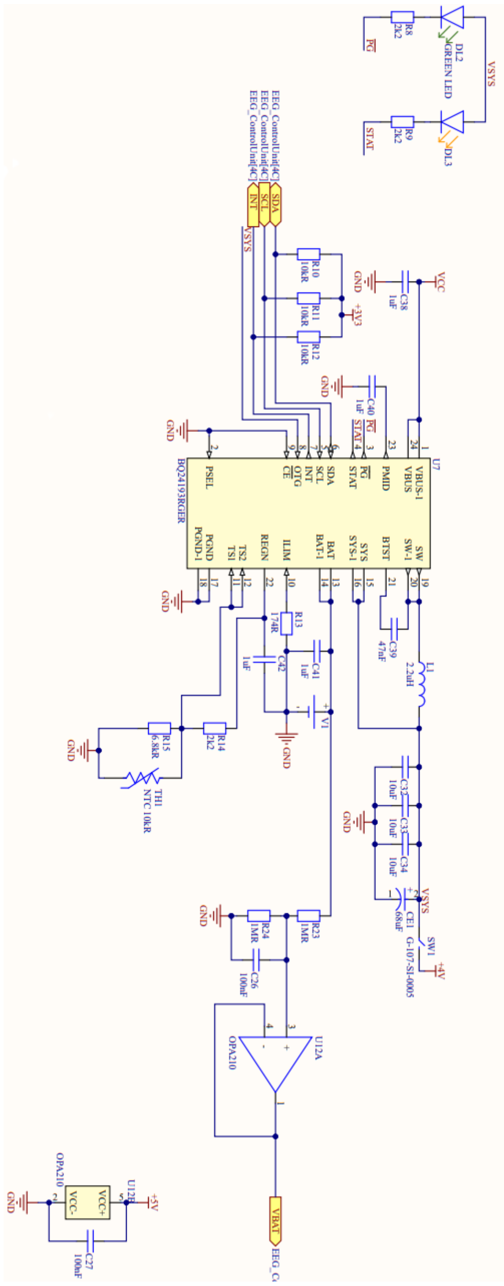

Figure 5.7: Circuit for the chosen charger

The component has a few interesting parts:

- The component uses I2C communication (signals SDA and SCL) with an MCU. The signals require pull-up resistors.
- TH1 is a thermistor that must be put on a battery so the device can be protected from overheating the battery during the charging up process.
- The MCU can be aware of the battery capacity thanks to a voltage divider (resistors R23 and R24). They have very large resistances to reduce the depletion of the battery. The voltage follower U12 protects the MCU in case the MCU is not powered up since the amplifier will not have power, either. It also protects against ESD with internal protection.
- Filtering passive components - capacitors and an inductor are at the output. Furthermore, a switch (SW1) is behind them. It is here because it can effectively turn off the device but still be capable of charging the battery inside.

Lastly, it is needed to adjust the voltage level for logic circuits, the analog part, and an SBC (Single Board Computer).

- 6x LDO to get 3.3V (1x for the logic on this board, 4x for each channel of cells, and 1x for a spare one which can possibly be used for a different device)
- 3x Inductor Built-in Step-up mini DC/DC Converter to create 5V. (1x for SBC and 2x for all channels including the spare one)
- 1x LDO to get 4.5V for amplifiers creating REF signal.

5.2.2 Grounding

Good grounding technique and proper return path can significantly reduce Electromagnetic Interference (EMI). It becomes much more essential for us since we are dealing with tiny signals, and this board will provide ground for all cells and even SBC.

To reduce interference from logic circuits and high-speed signals into the analog part, the ground was divided into two parts (see the image on the next page) and connected by net-tie in only one place. That will ensure that the ground in cells will be separated and the interference from logic circuits will be as minor as possible.

A connection like that may create a small potential between these grounds on cells. We have to make sure that the grounds are not connected anywhere else. Therefore, the selected components that combine digital and analog parts (in this case, only ADC) must not internally connect the grounds and must have tolerance for small potential between these grounds.

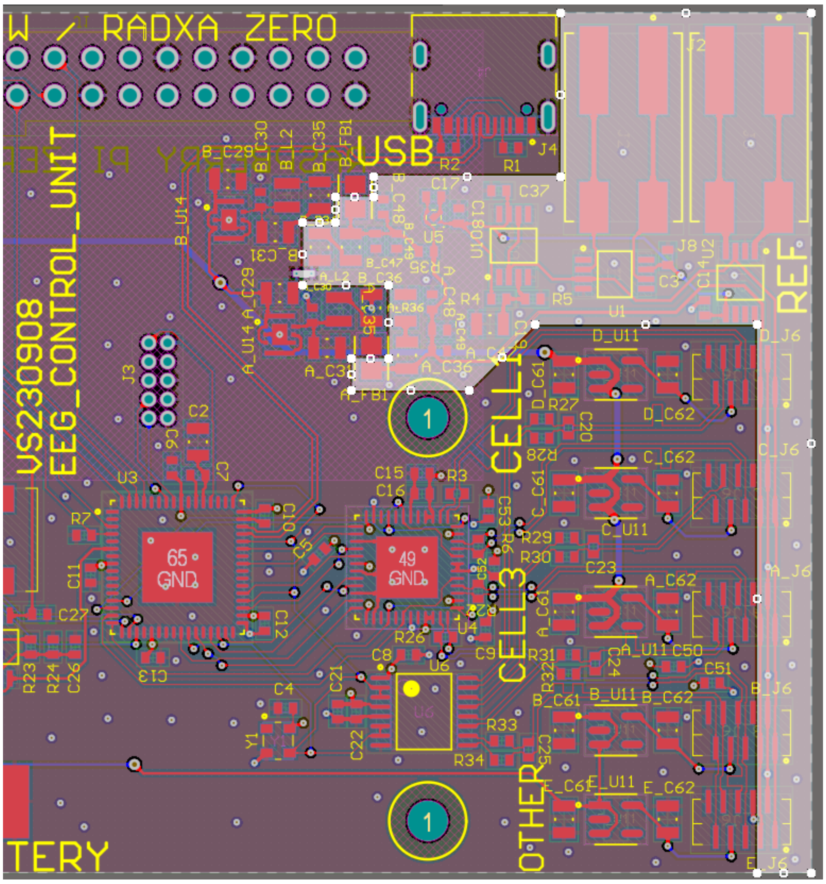

Figure 5.8: Split ground - highlighted is the analog ground

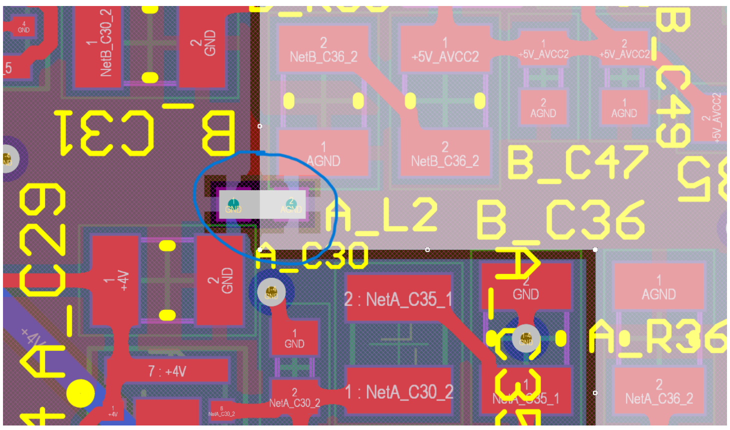

Figure 5.9: Net-tie connecting grounds - in the blue circle

5.2.3 Anticipated power requirements

The board must be capable of fulfilling power requirements for itself, all cells, and SBC. Therefore, we can assume maximal consumption from datasheets of individual components.

Estimated Maximal Current Consumption [mA]						
Main Board		Cell - analog		Cell - digital		SBC
MCU	29.4	ADC	7.7	MCU	3.1	1000
data transceiver	165	amplifiers	20.7	ADC	0.9	
clock driver	70	losses	2	receiver	25	
amplifiers	9.6			transceiver	22	
clock	7			LED	0.82	
Individual sum	251	30.4		51.82		1000
On 3.3V	241.4	7.7		51.82		0
On 4.5V	9.6	22.7		0		0
on 5V	0	0		0		1000
Sum on 3.3V, 16 cells	1193.72					
Sum on 4.5V, 16 cells	372.8					
Sum in [W]	10.62					

Table 5.1: Power Consumption

Used current consumption for the SBC was taken from Raspberry Pi Zero 2 W measurements, where maximal current spikes, while using WiFi, were 635 mA[J.on]. To that, a significant amount of reserve was added. Raspberry Pi Foundation recommends 2.5A, but it would be too high after seeing the measurements.

The overall maximal draw power would be 10.62 W. That is an amount that the board can handle with a considerable reserve. The board can deliver around 19 to 22.5 W. Therefore, there is enough reserve even for charging the battery during regular operation.

The actual average values from my measurements referenced to 4V are around 90 mA for Main Board, 50 mA for a Cell, and 200 mA for SBC.

5.3 Single Board Computer - SBC

Three SBCs can be used with this board - Raspberry Pi Zero W, Raspberry Pi Zero 2 W, and Radxa Zero. I will use Raspberry Pi Zero 2 W.

The board is designed in a way that the SBC can be directly attached to the bottom side of the board. Therefore, SBC is a piggyback board to the main board.

SBC is a powerful tool to enhance the board. The essential operation expected from SBC is to gather measured data and send them via WiFi to other devices. However, it can be used for much more depending on the needs of researchers working with the EEG device.

5.3.1 Communication

The communication between the Main Board and SBC is via SPI. Since the maximal SPI's clock speed is 100 MHz for the Main Board, it could theoretically reach the speed of 50 MHz (There must be at least two clocks per bit). The speed must be at least 12.5 MHz to transfer all measured data before the arrival of the fresh one. Experiments determined that the communication suffers from zero or minimal lost packets up to 15 MHz.

Setting	Value
Data Order	MSB first
Clock Phase and Polarity	SCK is low when IDLE. Leading edge - rising and sampling, Trailing edge - falling and changing
SPI Frame	basic frame without address
Character Size	8 bits
Clock Speed	$\geq$ 12.5 MHz

Table 5.2: SPI settings

The SBC is the host. Therefore, the host initiates all the communication. As seen in the Figure below, the length of one message is always 3457 bytes for both - master and slave. The main board gathers nine measurements and sends them to the SBC in one packet.

The CS pin is not used by SPI control. Instead, it is used as an indication to master that data are ready. Therefore, the master must look for the rising edge of the signal on the CS pin. After that, it can start transmitting. Otherwise, it can result in undefined behavior and possibly damage measurement data in the next cycle.

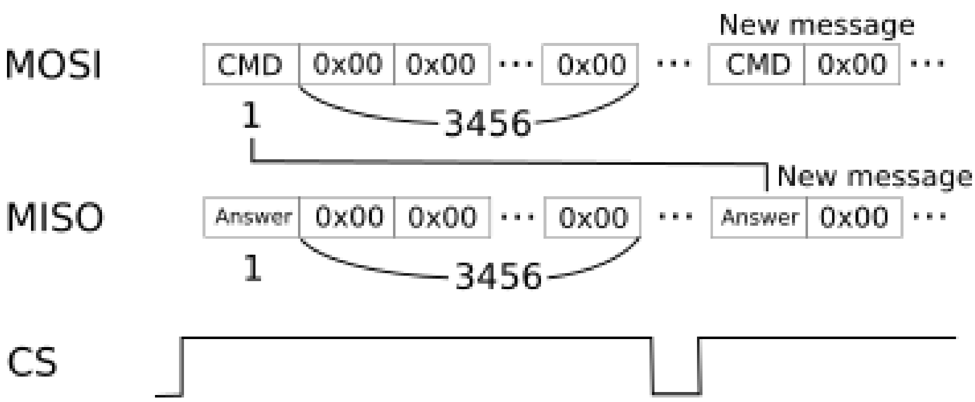

Figure 5.10: SPI Communication

The structure of one message for the master (MOSI) is one command byte (see the table below) and 3456 bytes, that can be anything since the slave does not check what is inside. The purpose is to provide a clock so the slave can send all its data.

Slave's message begins with one byte of an answer to **the previous** command and 3456 bytes of measurement data. Nine samples from all 16 cells are fused into one packet.

Command	Value	Answer	Value
BAT	0x00	Battery status - in %	0 - 100
NOISE	0x55	Acknowledgement - start the sin wave on Cells for a certain period	0xB4
OTHERS		Treat as command BAT	

Table 5.3: SPI communication commands and answers

5.3.2 Software on Computer

The software on the computer is only for testing of designed electronics. Therefore, only a bare minimum is required. The software should do the following:

- Connect to SBC via Wifi as a TCP Client
- Receive data
- Interpret data
- Save data to a file
- Real-time plotting of chosen channels/electrodes

The program was written in Python since its library for plotting, Pyplot, provides a straightforward way to display incoming data. The program must use threading to be capable of real-time operations, but the plotting must always be in the main thread since it provides GUI.

The user must first specify which electrodes will be displayed, how many samples will be displayed, and their indentation since they will be displayed in the same graph. The program will start receiving data via Wifi, interpret them, store them in a file, and display them in a plot. See the picture on the next page.

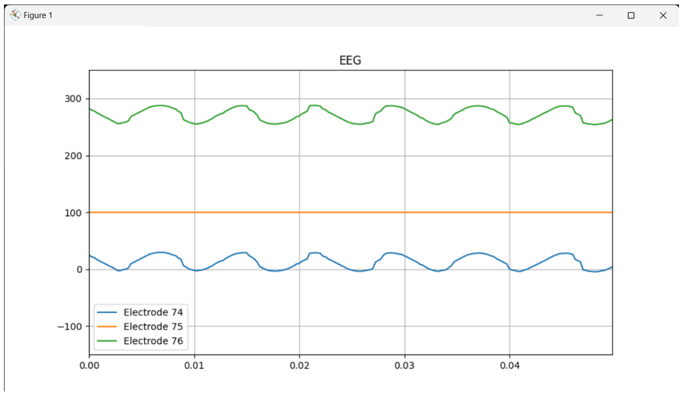

Figure 5.11: Real-time plotting of unconnected electrodes 74-76 to demonstrate created application.
The indentation of lines is 100. The vertical axis is % of possible ADC output (100% is a maximal positive number, -100% is a minimal negative number)
The horizontal axis is time in seconds since receiving data.

The interpretation is not very straightforward in Python since the variables are 64 bits long. Therefore, there is a guide on how to do it:

- Let us have incomingData[3], where the three bytes of the first channel are stored.
- Let us have a variable sign_bit = 1 « (24-1)
- Combine three bytes into one number:
  interpreted = (incomingData[0]«16) | (incomingData[1]«8) | incomingData[2]
- Check if the number should be negative (the first bit of 24 bits number is 1): if interpreted & sign_bit
- If it is positive, then it is finished. Otherwise, make the last step
- Make it negative:
  interpreted = (interpreted & (sign_bit-1)) - (interpreted & sign_bit)

5.4 3D View and BOM

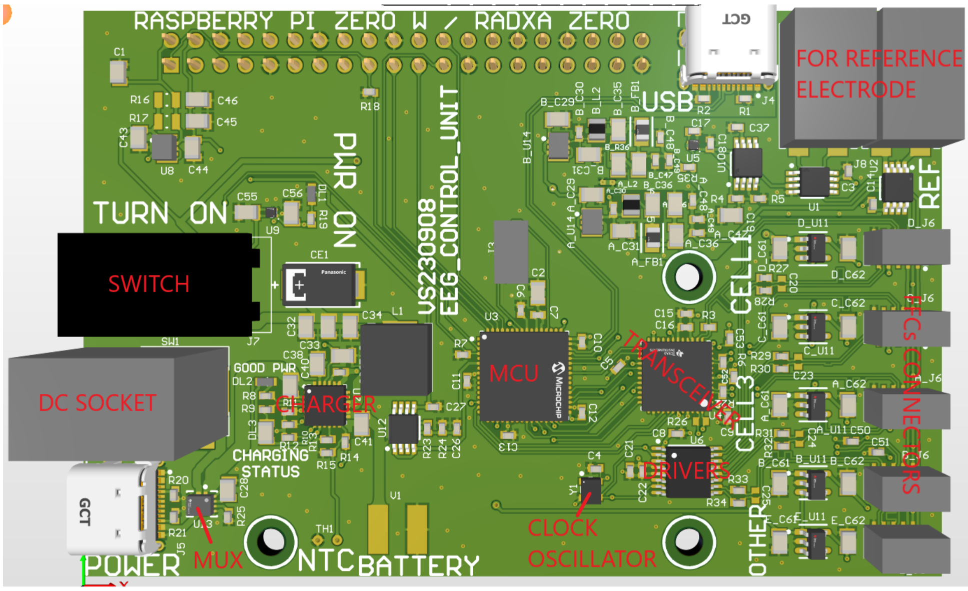

Figure 5.12: Model of the Main board - top View

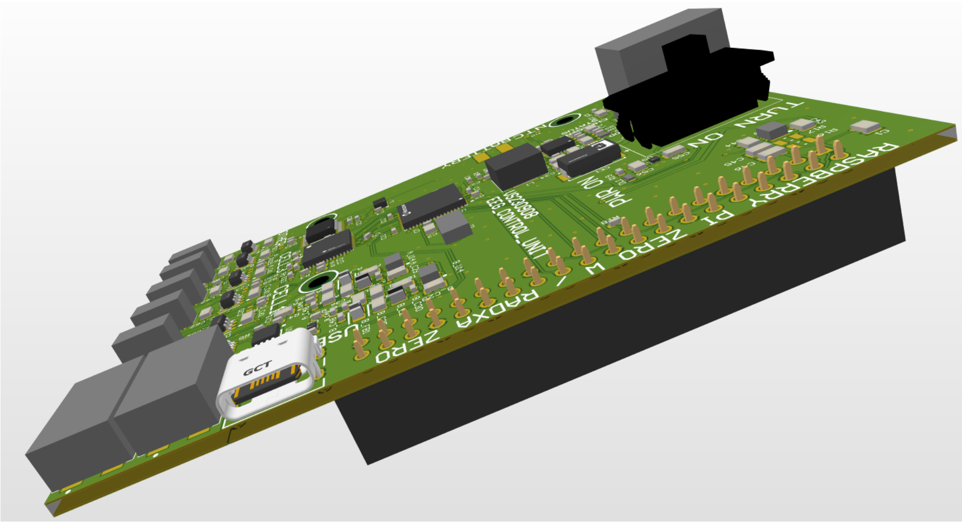

Figure 5.13: Model of the Main board - side View

Used components can be found in this table:

Name	Part Number	Quantity	Description
Ceramic Capacitor	GRM21BC8YA106KE11L	16	0805 35V 10μF $\pm$10% X6S
	GRM155R71H104KE14D	20	0402 100nF 50V $\pm$10% X7R
	GRM155R71H103KA88D	9	0402 10nF 50V $\pm$10% X7R
	CL21B105KBFNNNG	17	0805 1μF 50V $\pm$10% X7R
	GRM155R70J105KA12D	2	0402 1μF 6.3V $\pm$10% X7R
	CGA4J1X7R1H475K125AC	1	0805 4.7μF 50V $\pm$10% X7R
	GRM1555C1H102JA01D	2	0402 1nF 50V $\pm$5% C0G
	CC0805MKX6S4BB476	1	0805 47μF 4V $\pm$20% X6S
	MC0402B473J250CT	1	0402 47nF 25V $\pm$5% X7R
Tantalum Polymer Capacitor	16TQC68MYF	1	68μF 16V ESR 50mΩ
Resistor	MCWR08W1R00FTL	2	0805 1Ω 1% 1/8W
	MCWR04X5101FTL	4	0402 5.1kΩ 1% 1/16W
	MCSR04X1000FTL	4	0402 100Ω 1% 62.5mW
	MCSR04X104JTL	3	0402 100kΩ 5% 62.5mW
	MCWR04X2201FTL	3	0402 2.2kΩ 1% 1/16W
	RC0402FR-0710KL	4	0402 10kΩ 1% 62.5mW
	ERJ-2RKF1740X	1	0402 174Ω 1% 0.1W
	WR04X6801FTL	1	0402 6.8kΩ 1% 0.063W
	MCSR04X102JTL	1	0402 1kΩ 5% 0.0625W
	RE0402BRE071ML	2	0402 1MΩ 0.1% 62.5mW
	MCWR04X2202FTL	1	0402 22kΩ 1% 1/16W
	CRCW04020000Z0EDC	9	0402 0Ω 1/16W
Inductor	74479276222C	2	2.2μH 1.6A shielded
	PCMB063T-2R2MS	1	2.2μH 8A 20%
Ferrite Bead	BLM21PG331SN1D	2	330Ω 25% 100MHz 1.5A 70mΩ DCR 0805
Connector	0781191020	5	FFC, 10 Positions, 0.5mm, Straight, Surface Mount
	2060-452/998-404	2	Push-in, SMD, 0.75mm^2, 9A, 2 Positions
	USB4105-GF-A-060	2	USB CONN, 2.0 TYPE C, RCPT, 16POS, SMT
	FC681465	1	Power, Solder, Through-Hole, 2.1mm or 2.5mm input
LDO	TPS7A2033PDBVR	5	SOT23-5, 3.3V, 300mA, ultra-low noise
	TPS7A2033PDQNR	1	XDFN4, 3.3V, 300mA, ultra-low noise
	TPS7A2045PDQNR	1	XDFN4, 4.5V, 300mA, ultra-low noise
Step-up Mini Converter	MYRBP500080B21RE	3	DC/DC Converter, 600mA, 5V
LED	KPHD-1608LVCGCK	2	Chip LED, Green, 8mcd, 0603, SMD
	KPT-2012LVSECK-J4-PRV	1	Chip LED, Orange, 50mcd, 605nm, 0805, SMD
Header	SFH11-PBPC-D20-ST-BK	1	40 Positions, Dual Row, 2.54 mm Pitch, Straight, Female
	2199SB-10G-301523	1	10 positions, Dual Row, 1.27mm Pitch, Straight, Male
Switch	G-107-SI-0005	1	Slide, Enclosed Micro-Mini, SPST, ON-ON
Thermistor	103AT-4-70374	1	NTC, 10kΩ, 1%, Shape 1, 30 AWG, 50mm
MCU	ATSAMD51J20A-MU	1	32-Bit ARM Cortex-M4F RISC 1MB Flash 1.71-3.63V
LVDS	SN65MLVD040RGZT	1	TRANSCEIVER, 4/4, 48VQFN, 250 Mbps
	SN65MLVD047APW	1	4/0, 16-TSSOP, 200 Mbps
Charger	BQ24193RGER	1	4.5A single cell, Narrow VDC Power Path, 24-VQFN
Multiplexer	TPS2121RUXR	1	2.7-22V, 56mΩ, 4.5A, power mux with seamless switchover
Clock Oscillator	DSC1001DI5-008.1920T	1	8.192MHz, MEMS Oscillator, Low Power, 10ppm, 4-VDFN

Table 5.4: List of components for Main Board

Chapter 6

Electrodes

The important part of an EEG device is not only the electronics, but electrodes are no less important. It is crucial to ensure electrodes have low impedance since it makes useful signals less noisy. However, that does not mean the measurement with higher impedance electrodes would be useless. It is also important to ensure the electrodes have similar impedance since the one with higher impedance would be noisier, rendering the overall measurement lower quality.[J.fF]

The department provided the electrodes used on this device. Their structure consists of three layers: a plastic base with a silver (Ag) layer coated by silver chloride (AgCl). That is the most common structure of electrodes and functions very well with the designed electronics.

The means to reduce impedance in the designed device is salinated water. The electrodes contain a sponge that releases water over time and thus keeps roughly the same environment even for longer experiments. It also improves the feeling while wearing them, which can be highly individual.

The electrodes have a cylindric shape. The diameter is 1 cm, and the cover adds around 1 mm.

There will be 128 electrodes, which need careful deployment so the measured signals can be easily associated with brain functions. The layout was defined beforehand since the department will also provide the cap. The simulation from placement can be seen in the picture on the next page.

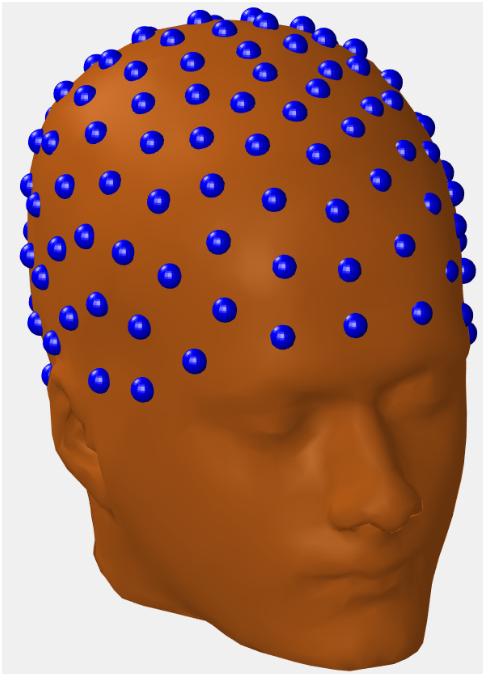

Figure 6.1: The layout of electrodes on a head
Picture provided by the thesis supervisor

Chapter 7

Cap

The cap was transformed into 2D plates that create areas like these:

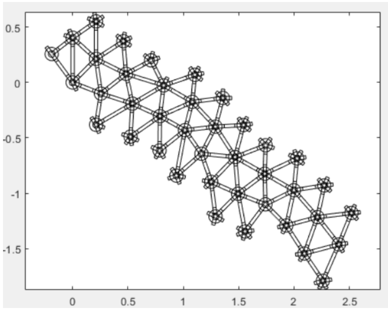

Figure 7.1: The cap spread into 2D
Picture provided by the thesis supervisor

They are created from silicone and cut by a laser. The individual plates are connected by glue, forming the whole cap.

Figure 7.2: The provided cap to try the designed device
Picture provided by the thesis supervisor

The last step with the prepared cap is to place electrodes on it. The department created and provided the cover for designed electronics. Thus, the placement is much easier because once it is put into the cover and internal wires are soldered to the pads for incoming electrodes on cells, the wire from an electrode can snap onto a magnet on the cover. It will need more testing and maybe even pouring a material like silicone over the electronics, but that can be a subject for improvement for the successors of this thesis.

Figure 7.3: The cap with electrodes without electronics
Pictures provided by the thesis supervisor

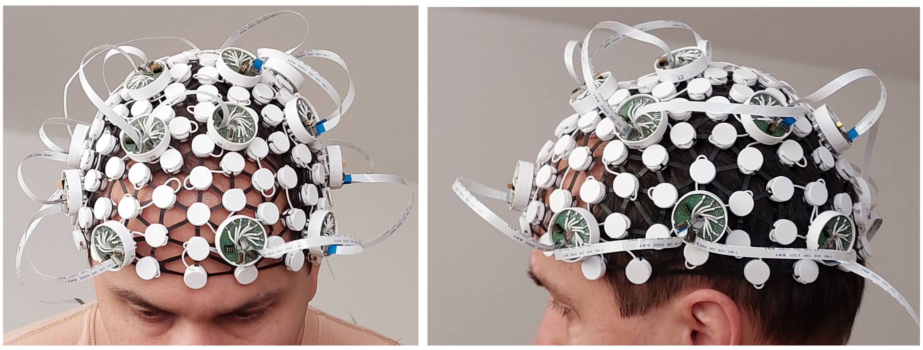

Figure 7.4: The cap with electrodes and a designed cells
Pictures provided by the thesis supervisor

Chapter 8

Measurements With The Developed Device

Several measurements were performed to test the newly developed device. Firstly, the most critical measurement is the input noise since if it is too high, it would not be possible to recognize the useful signals from the noise, and the whole electronics would have to be redesigned.

The measurement of input noise is done by connecting the input to the reference (REF). Most EEG signals are up to 100 Hz, so the frequency band for this measurement is 100 Hz.

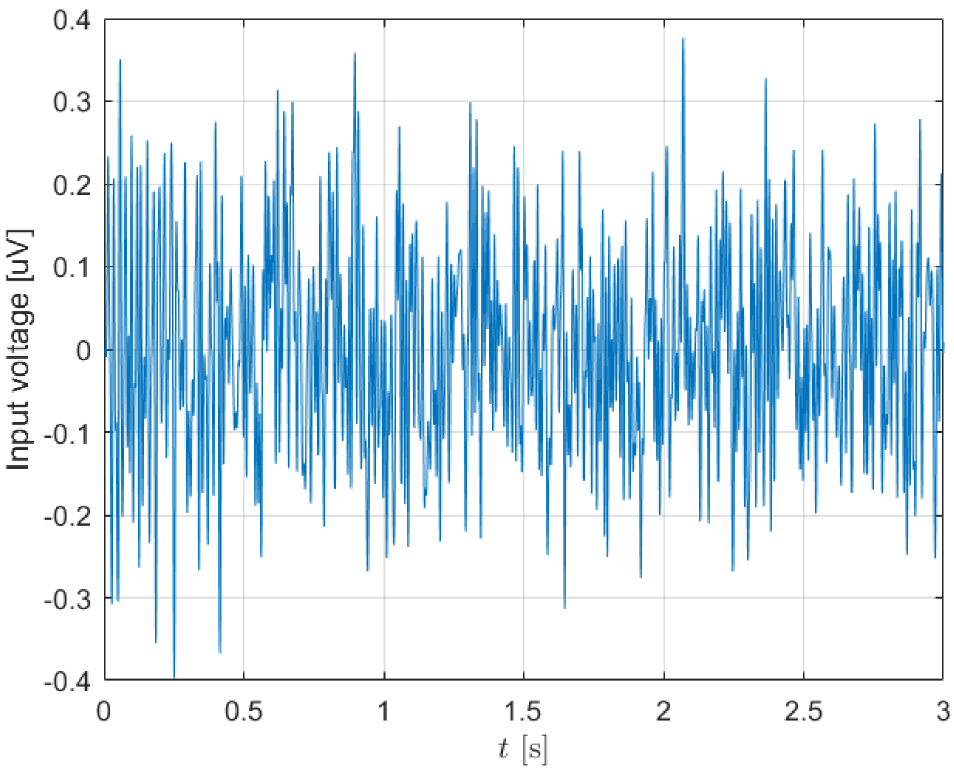

Figure 8.1: Input noise with connected reference to the input

The peak-to-peak is 0.8 μV. Since the measured signals are expected to have amplitudes in tens of microvolts, the input noise is sufficiently low to measure them. That confirms the usability of the newly developed device and can be tested on body signals.

The device can be used for measuring different body signals, not only EEG. Therefore, the first graph of this part is an electrocardiogram (ECG).

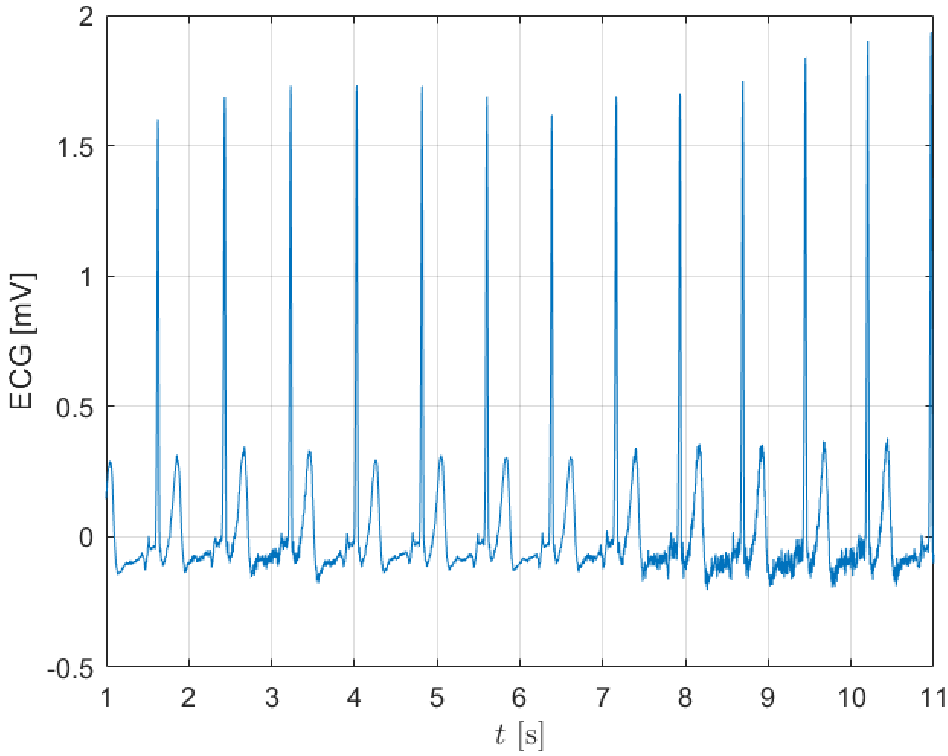

Figure 8.2: ECG measured on the thorax

The measurement of ECG looks as expected. The fundamental waves (P, R, T) are well-visible in the graph. The muscle activity due to breathing is in the second half of the graph. Breathing is also causing changes in the heartbeat.

The device was primarily developed as EEG, so the subsequent measurement was done with one electrode in the occipital lobe. That part of the brain is responsible for visual perception and can be found in the back of the head. The reference electrode was placed on the forehead.

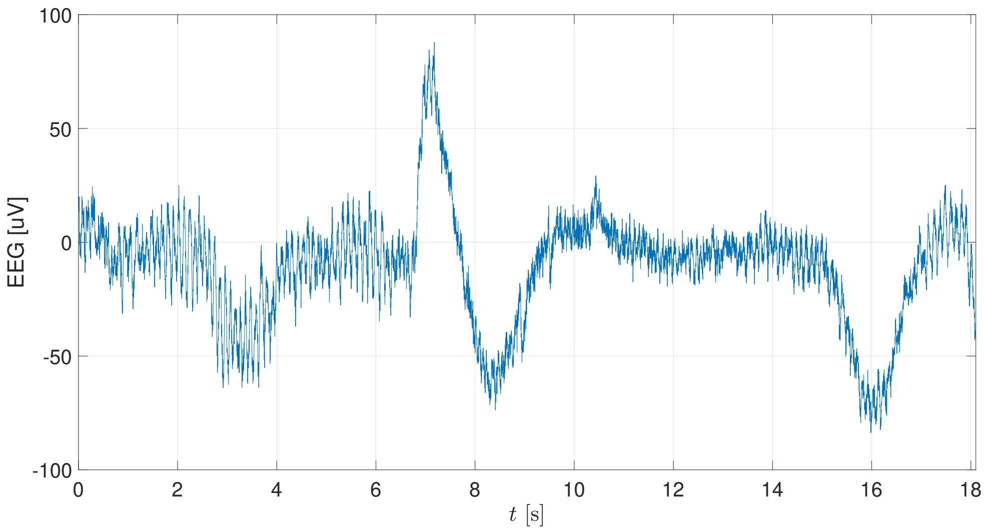

Figure 8.3: The record of EEG. The subjects' eyes were closed until 6.7 seconds, and then they were opened.

The subjects' eyes were closed at the beginning and were opened at 6.7 seconds. The alpha activity is visible before opening the eyes. Also, the subject was not entirely relaxed, so the record contains minor artifacts from muscle activity.

The penultimate measurement has the same placement of electrodes as the previous one, but this time, a visual evoked potential (VEP) is measured. A small green LED (KPHD-1608LVCGCK) is turned on each 500 ms and stays on for 50 ms.

The resulting signal (blue line) was created by averaging 259 responses to the blinking LED. The response to the stimulus starts around 90 to 100 ms after the stimulus. The grey lines are confidence intervals calculated with the rule of three sigmas without the correction for multiple tests.

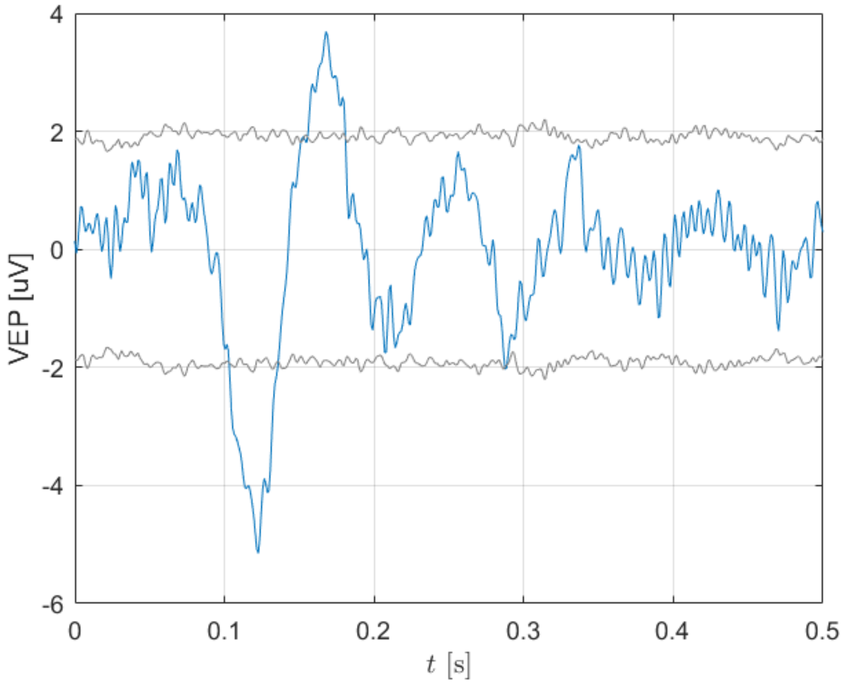

Figure 8.4: The record of EEG for VEP with a blinking LED.
The blue line is a signal, and the grey lines are confidence intervals.

The last measurement uses the whole device, as seen in the picture 7.4. The signals of individual electrodes were indented to show them in one graph. The signals of poorly connected electrodes were removed.

Figure 8.5 on the next page depicts the measurement part where the subject has closed eyes at the beginning and opens them in the 68th second. The alpha activity is visible before the opening of the eyes, too, and disappears afterward. The subject repeatedly blinked between the 72nd and 74th second and clenched its jaw around the 76th second. These movements result in significant blink and muscle artifacts.

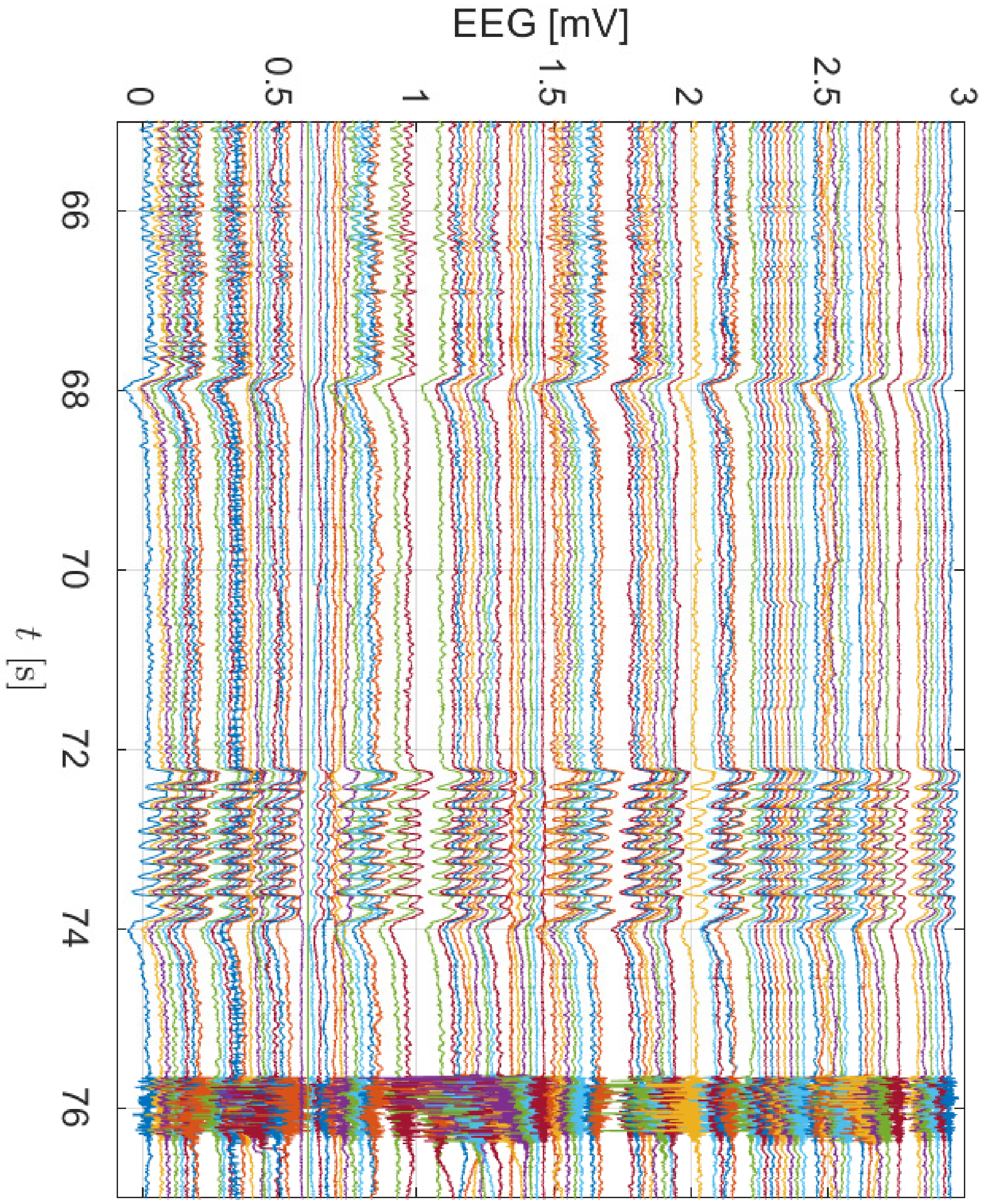

Figure 8.5: Record of EEG with high-density electrodes

Chapter 9

Price evaluation

One of the stated goals was to make this device relatively cheap compared to commercially available models. Therefore, this chapter will provide an insight into the finances spent on this project. The prices will not be exact but always rounded to higher numbers, sometimes even with a reserve. The price of the prototype, damaged components, and other mistakes will be omitted.

Item	Price [$]
Control Unit	
Components with spare ones	590
PCB	35
SBC	30
Total	655
16 EEG Cells	
Components with spare ones	530
PCBs	35
Total	565
Others	
Cables	35
Electrodes	20
Cap	15
Covers for electronics and electrodes	15
Medical power supply	25
Battery	20
Total	130
Overall	**1350**

Table 9.1: Price of the developed EEG device

The overall price with spare components and a reserve is $1350. It means that the developed device is even cheaper than buying a cap with electrodes (depending on where it would be bought). It also means the stated goal is fulfilled.

The price is only about the material and in case of individual purchase. A company could significantly save money on that in case of mass production. However, the company would pay wages to people working on the device, and probably the most expensive item would be getting a certification.

Chapter 10

Ideas for improvements

Despite the age of the EEG device, its development is still ongoing, and the same is true for this newly developed device. Therefore, a few ideas of improvements that can be made to this device will be shared with anyone who would like to continue on this thesis or just take inspiration.

There are probably no significant improvements for the cell at this moment since it meets the expectations completely. The only change that could improve convenience for production is the connection of electrodes. Soldering a wire to a small area with other components and vias being so close may be problematic for mass production. Therefore, it could be beneficial to find a suitable connector for electrodes. Nevertheless, it will not be an easy task since the space is extremely limited.

It should be possible to make the control board smaller. There are two other ways besides shrinking itself and choosing smaller packages. The board has two connectors for a reference electrode. It was made this way for testing purposes with different amplifiers. Only one is used during operation. Therefore, one can be removed, which would save not only space but some money, too. The second way is to either choose a more miniature switch or connect the switch externally just by two wires. Therefore, choosing a suitable connector may result in needing less space. The switch would probably end up somewhere on the package to be convenient to the user, but it would have to be connected externally.

The USB is currently being used only for testing purposes during development. It could be advantageous to find a different purpose, too. One idea would be to add EEPROM communicating via I2C with the processor since the SPI is used with SBC, and there is no capacity for another device. The I2C would be shared with the charger, which is completely fine. The EEPROM could hold diagnostics data, and in case of establishing the connection via USB, it could send the data to a serviceman's computer to quickly spot any problems that do not concern the main power supply.

The last improvement in hardware could be in the SBC. There are many options. If a successor would use the board in the same way just to send the data through Wifi, then it could be implemented on the main board, which would eliminate SBC. It would significantly reduce the price since it costs around $37.

The usage of the SBC could be extended through a display showing basic information like battery status and connection. Maybe you could use it to set the charger differently or even show a signal plot from an electrode. It offers many opportunities. Moreover, having a display provides a feeling of luxury to a customer.

The case for the Main Board has not been designed yet. There are suggestions for two options - either wearing the board in a case around the neck or creating a water-resistant cover and attaching it somewhere to the cap. A water-resistant cover may be hard to achieve due to the cables from cells, but every challenge provides an opportunity, and a skilled mechanic engineer might find a way.

Created application for computer contains only bare minimum, and it is not user friendly. Therefore, significant improvement can be made by designing an application that would easily allow to change settings and decide which electrodes should be shown, maybe by check box or better with a 3D model of the head where you would be able to click on the desired electrodes. Creating a real-time 3D map from measurements in a brain model could also be interesting.

Chapter 11

Conclusion

Electronics for the Electroencephalograph was divided into two parts - EEG Cell and Main Board. Eight electrodes are connected to each Cell. The Cell handles the measurements and converts them from analog to digital with a sampling rate of up to 4000 Hz. Several cells are connected to each other and eventually to the Main Board, which communicates with the cells via USART using Low-Voltage Differential Signaling (LVDS) to enhance noise resistance. Firstly, a prototype was created to test ideas and hardware. A pilot version was designed based on the prototype version with needed changes. The Cells were designed to be very small to fit into a cap alongside the electrodes.

A Single Board Computer (SBC) is connected to the Main Board as a piggyback. Raspberry Pi Zero 2W was chosen for this purpose, but it is possible to connect different boards, too. The SBC receives measurement data, saves them on an SD Card, and transfers them via Wifi to a connected recipient. A simple application with real-time plotting in Python was created to test it.

Electrodes were designed to be semi-dry, so they use saline water to increase the conductivity between skin and electrodes. The design can handle 128 electrodes (+ one as a reference electrode connected to the main board). Therefore, the design uses 16 Cells.

Covers for electrodes and the developed electronics were eventually provided by the department, together with a cap. Therefore, designing them is out of the scope of this thesis. Everything was designed so that the cap with electronics could be put into saline water to make it wet and then put on the head of the patient, significantly reducing the time needed for preparations.

Measurements were provided to test the developed device and show its capabilities. The measurements record not only EEG but also ECG to demonstrate its ability to measure other body signals.

Possible improvements and extensions to this work are provided for possible successors at the end. That should provide enough ideas for anyone who would like to continue in the development of this device.

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