Development of Modular EEG Framework for Teaching, Training, and Data Collection

Final Year Project Report

by

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DECLARATION

We hereby declare that this project report entitled “Development of Modular EEG Framework for Teaching, Training, and Data Collection” submitted to the School of Electrical Engineering and Computer Sciences (SEECS), is a record of an original work done by us under the guidance of Dr. Faisal Shafait and Mr. Imran Abeel and that no part has been plagiarized without citations. This project work is submitted in partial fulfillment of the requirements of the degree of Bachelors of Electrical Engineering.

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DEDICATION

We would like to dedicate this work to Almighty Allah, our parents, and our respected advisors, Dr. Faisal Shafait and Mr. Imran Abeel.

ACKNOWLEDGEMENTS

We would like to wholeheartedly thank our advisor Dr. Faisal Shafait and the co-advisor Mr. Imran Abeel for helping us throughout the final year project. Without their keen guidance and support, it would not have been possible for us to meet the scope of the project in time. This project has been funded by German Academic Exchange Program (DAAD).

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ABSTRACT

Epilepsy is a disease characterized by the unexpected occurrence of seizures. It is one of the most prevalent neurological disorders and affects around 50 million people worldwide [1]. It is estimated that 1% of the population in Pakistan suffers from epilepsy, i.e., about 2 million people. This is equal to 10% of the world burden of epilepsy [2]. However, there is a dearth of both trained neurologists and EEG diagnostic and recording facilities. Since approximately 75% of neurologists are concentrated in the three major cities of the country, many patients suffering from epilepsy in rural areas have no access to appropriate medical diagnosis and treatment.

Electroencephalogram (EEG) recordings are the major tool for diagnosing and monitoring epilepsy by detecting problems in brain activity. Furthermore, EEG recordings are useful for the identification of other disorders like dementia, meningitis, stroke and coma.

In Pakistan, particularly in rural areas, the quality and reach of neuropathic caregiving is very dismal. Portable at-home diagnostics have been identified as a key technology of a digital revolution in the healthcare system. In this regard, we have developed a low-cost wearable wireless EEG recording device titled "sEEGs" based on open-source components and designs. The device records parameters, including EEG, motion, and electrode-skin impedance. Using this device, non-expert users/ caregivers can capture good quality EEG signals.

Furthermore, the data will be wirelessly transmitted to a smartphone app as well as a PC for visualization. There are plans to collect a curated EEG dataset from Military Hospital Rawalpindi for use in Artificial Intelligence based analysis/diagnostics. The analysis of these EEG recordings will provide the pre-diagnosis screening to separate normal EEG from abnormal EEG, whereby the detection of abnormal EEG would mean that the patient needs to see a specialist neurologist for proper diagnosis. The capability to provide such pre-diagnosis in rural areas is expected to have a tremendous socioeconomic impact on the neurological healthcare scenario in Pakistan.

Chapter 1

INTRODUCTION

Electroencephalography (EEG) is widely used in clinical practice because of its low cost and its lack of side effects. It is used to detect problems in the electrical activity of the brain that may be associated with certain brain disorders. In particular, non-invasive, scalp-recorded EEG is of utmost importance in the diagnosis of epilepsy [3]. Furthermore, it is also used for the selection and monitoring of pharmaco-therapeutic intervention. Traditional EEG technology consists of bulky hardware and requires a computer for data acquisition. Moreover, signal acquisition requires application of fragile wired sensors on the scalp with the help of an elastic cap, and expert knowledge is necessary to apply EEG caps and record diagnostically useful signals.

However, in recent years, developments have been made to produce small, wireless EEG acquisition systems which are suitable for home-based EEG acquisition [4, pp. 1617-1621]. Secondly, smartphone use, and portable at-home diagnostics have been identified as two key technologies of a digital revolution that will change the healthcare paradigm. Keeping these two developments in mind, we have developed an intelligent electroencephalogram (EEG) acquisition and diagnostic system to facilitate the diagnosis and treatment of prevalent mental illnesses, such as epilepsy, in rural areas of Pakistan, where the reach and quality of neuropathic care-giving is rather dismal.

For this purpose, we have developed a low-cost wearable recording device based on open-source components and designs. The final device will record multiple physiological parameters, including EEG, motion, and electro-dermal activity. This device will be combined with EEG electrodes for capture of good quality EEG signals by non-expert users/caregivers. In addition, a smartphone based intelligent EEG acquisition app will be developed, enabling data acquisition from wireless EEG/electrophysiological sensors and subsequent transmission to backend servers for Artificial Intelligence based analysis/diagnostics. The analysis of these EEG recordings will provide the pre-diagnosis screening to separate normal EEG from abnormal EEG, whereby the detection of abnormal EEG would mean that the patient needs to see a specialist neurologist for proper diagnosis. The capability to provide such pre-diagnosis in rural areas is expected to have tremendous socioeconomic impact on the public by making neurological healthcare more accessible. This device can also be used in laboratories by researchers who are conducting EEG related experiments.

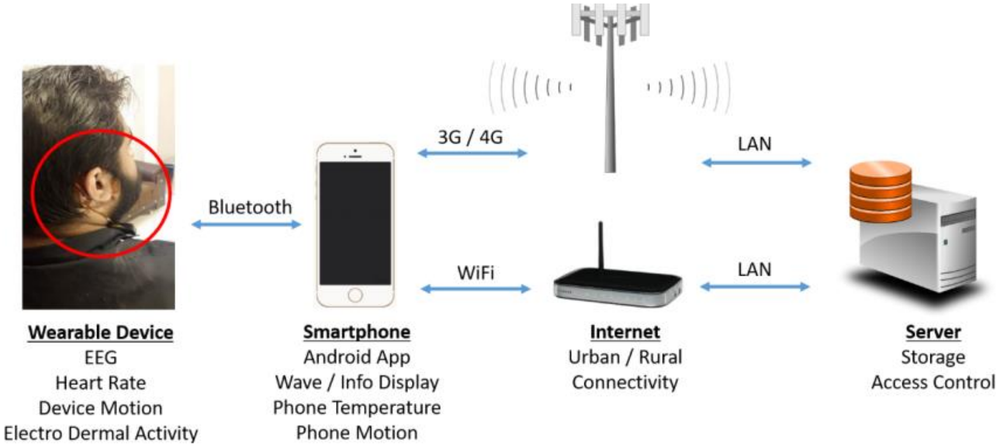

Figure 1: A concept image of the final monitoring system

1.1 Outline of the Report

This report comprises eight other chapters, each of which focuses on a specific portion of the final year project.

- Chapter 1 explains the unmet need of the society, project's purpose, scope and the customers it targets.
- Chapter 2 explains all the previous research work that has been put into this work and a background knowledge of the related work that has been done and published as journals, papers, websites etc.
- Chapter 3 defines the problem statement in detail, providing all the technical difficulties and problems faced and what solution is being provided in this regard.
- Chapter 4 provides the solution to the problem and what methodology has been adopted in developing that suggested solution.
- Chapter 5 states all the design constraints and the architecture adopted for developing the solution. This will help the readers to understand the technicalities of the project in a much better way.
- Chapter 6 provides the readers with all the implementation and testing details along with the screenshots of the actual implementation and testing done on the application being developed.

- Chapter 7 discusses all the results obtained from the implementation and how they are in accordance to the original objective of our project.
- Chapter 8 discusses all the future aspects and work that can be done to further improve this system and maintain it.
- Finally, a bibliography is provided of the sources referred to in compiling this work.

Chapter Summary

This chapter gives an introduction to the devised system after providing some context to the pertinent problems that Pakistan has been facing in terms of poor quality and reach of neuropathic healthcare. Using an open-source design, the devised system is a low-cost solution for EEG data acquisition by non-experts. Artificial intelligence-based pre-diagnosis can be conducted on data from this device to provide insight on whether the data is normal or abnormal. An overview of the entire report is also presented.

Chapter 2

LITERATURE REVIEW

The increase in interest in Brain-Computer-Interfaces (BCI) has led to a surge in the development of Electroencephalogram (EEG) headsets. Products like g.tec HIamp and Smarting are commercially available and provide high quality signal acquisition. However, they are very expensive which hinders their usage at a mass level. Table I [5] provides a price and specification analysis of different commercially available EEG devices.

Table I: State-of-the-art professional brain–computer interface (BCI) systems [5]

System	Sampling Speed, Hz	# of Channels	Accuracy	CPU	Electrodes	I/O	CMRR	Price €
g.tec [7] Nautilus	500	64	24-bit, <60 nV (LSB), <0.6 µV RMS	TI DSP	Active-dry/gel	Wireless 2.4 GHz/USB	>90 dB	>4.5 k
g.tec HIamp	38.4 k	256	24-bit, <60 nV (LSB), <0.5 µV RMS	TI DSP	Active-dry/gel	USB	>90 dB	>31 k
TMSi [8] Mobita	2000	32	24-bit, <24 nV	N/A	Passive dry	Wi-Fi IEEE 802.11 b/g	>100 dB	N/A
TMSi [9] Porti	2048	32	22-bit, <1 µV RMS	N/A	Active-shielding	Bluetooth/ optic fiber	>90 dB	N/A
TMSi Refa	2048	136	22-bit, <1 µV RMS	N/A	Active-shielding	Optic fiber	>90 dB	N/A

Due to the expensive nature of these devices, there has been interest in developing a low-cost EEG recording device which can acquire high quality brain signals. A large number of these designs use the ADS1298/1299 by Texas Instruments [6] as an analog front end due to the number of supported channels, 24-bit resolution, noise reduction, and programmable gain and sampling rate. We have discussed some significant works below.

Pinho et al. produced a 32-channel wearable and wireless EEG device for continuous ambulatory monitoring of epilepsy patients [7, pp. 1-7]. Active dry electrodes are used along with ADS1299. The sampling rate can be set as high as 1000 sps and the data acquisition module is based on the IGEP COM embedded system development platform. The data can be processed in real time over an ARM processor and also be sent via Wi-Fi to a PC for further analysis. However, despite being developed for long-term monitoring, the device has a battery life of 25 hours. Furthermore, the use of active electrodes was necessary because of the size of the device which is a downside.

Feng et al. presented EEGu2 which was an embedded device for EEG data acquisition [8]. They utilized a 16-channel cape for a BeagleBone Black development board which utilized 2 sets of ADS1299 and an ARM processor for on-board processing. This device collected data at 1000 sps. The intended use of the cape was to charge the device. However, it produced only 5% of the power consumed by the device.

Tri Thong Vo et al. presented an 8 channel EEG acquisition device which also used ADS1299 by Texas Instruments [9]. The product was oriented towards decreasing the cost by using a System on Chip (SoC) design which reduced the required circuitry. The device succeeded in achieving low cost, small design, and low power consumption. However, it only has 8 channels, and it cannot be expanded which is a major downfall.

Nathan et al. presented a 16 channel EEG acquisition device with dry electrodes for continuous monitoring of epileptic patients at their homes [10, pp. 1-2]. The device sends raw EEG data to a PC via Bluetooth for processing. In order to validate the working of their device, they have used BCI paradigms like P300 speller, steady-state visual evoked potential (SSEVP) and motor imagery tasks. They conclude that the successful validation of the device with these paradigms will allow physically disabled individuals to communicate.

OpenBCI is a community of researchers who are developing Brain-Computer-Interfaces with the ideology of being low cost and accessible [11]. The Cyton board has been found to perform on par with commercially available medical grade EEG equipment when tested for workload classification accuracy and correlation on P300 speller [12]. It is popularly used by researchers who are working on BCI based applications. Furthermore, their open-source visualisation software is also utilised by different researchers.

Uktveris and Vaicus presented a 16-64 channel EEG acquisition board based on ADS1298 [5]. They use a modular design which allows for vertical stackability of the boards. The sampling rate can be set between 250-1000 Hz, an atmega microcontroller is used and the data can be transferred using Wi-Fi or Bluetooth. However, the microcontroller does not have in-built Wifi, and Bluetooth capabilities and external modules have to be attached which increase the bulkiness. Furthermore, the device has mostly been validated for EMG signals and not the intended EEG signals. The source code and PCB files are not open source and cannot be externally verified. They have performed a comparison of the specifications of previous EEG acquisition systems which is shown in Table II.

Table II: Comparison of existing EEG acquisition boards [5]

Property	Proposed System	Pinho et al. [10]	Campillo et al. [14]	Boquete et al. [33]	Myung et al. [24]
Modular	Yes	No	No	No	No
Channels	64	32	8	8	16
Sampling frequency, Hz	1000	1000	500	400	512
Electrodes	Passive dry	Active dry	Passive dry	Ag/AgCl adhesive	Wet gel
Resolution, bits	24	24	12	12	24
I/O	BLE 4.0, Wi-Fi 802.11 b/g/n	Wi-Fi 802.11 b/g/n	UART	Zig-bee 802.15.4	Wi-Fi 802.11 d
CPU	Atmega2560	DM3730	MSP430	Atmega2560	STM32F103
Clock frequency, MHz	16	1000	12	16	72
CMRR, dB	−110	−115	−94	-	-
Max gain	12	24	12	10 k	-
Datastore	MicroSD	MicroSD	No	No	No
Local processing	No	Yes	No	No	No
Power, mAh	250	500	-	100	80

In terms of signal quality of various devices, Radüntz compared 6 different EEG devices in order to evaluate the conditions which result in optimum signal quality [13]. 60-minute recordings were collected for 24 individuals daily for 6 days to collect the data for signal quality analysis. For time domain analysis, the signal to noise ratio (SNR) was evaluated, along with the percentage of samples which were contaminated with artifacts. For frequency domain analysis, the band power variation was considered. The results showed that gel-based EEG systems had the highest signal quality. A summary of the results from the paper is shown in Table III.

*Table III: Signal quality results of tested EEG devices (***: $p \leq 0.001$; **: $0.001 < p \leq 0.01$; *: $0.01 < p \leq 0.05$) [13].*

Device	EPOC	Trilobite	Jellyfish	BR8+	g.SAHARA	g.LADYbird
Proportion of artifacts [%]	25.11	41.14	22.36	51.22	16.21	3.19
SNR [dB]	−13.66	−11.55	−14.31	−3.78	−0.50	5.09
Berger effect	*		–	***	***	***
Increase in frontal theta			**			*
Decrease in parietal alpha				**	**	***

Given the prolonged process of EEG diagnosis and lack of neurologists available in Pakistan, the best solution is to automate this resource-hungry process. Data collected from these EEG acquisition systems can be used for diagnosis EEG diagnosis can be helpful in improving neurological rehabilitation [14, pp. 100-108], diagnosing depression [15, pp. 1239-1246] and warning patients of upcoming seizures [16, pp. 1-7].

Chapter Summary

This chapter provides an overview of the existing attempts at developing low-cost EEG acquisition systems as well as their specifications and shortcomings. It is noted that most implementations utilize the ADS1299 ADC by Texas Instruments. The comparison of electrodes for signal quality and the potential applications of EEG signals in AI based diagnosis are also briefly discussed.

Chapter 3

PROBLEM DEFINITION

Non-invasive, scalp-recorded EEG is of utmost importance in the diagnosis of epilepsy [3], in addition to being used for the selection and monitoring of pharmaco-therapeutic interventions. In developed countries like Germany, children suffering from epilepsy regularly visit local hospitals to receive routine-EEG check-ups. However, in Pakistan, the situation is very different.

A study conducted in 2007 found that 66% of epileptic patients in Pakistan were managed by unqualified persons and only 12% of the patients received appropriate treatment [17, pp. 74-78]. As a result of this treatment gap, only 20% of school-going aged epileptic children were regularly going to school, and about 70% of the patients felt embarrassed by epileptic seizures and hid it from others. Epilepsy is a serious brain disorder that affects not only the individual but has a deep impact on the family and society in general.

EEG diagnosis is a time-consuming and resource hungry task which requires neurologists to constantly observe the patterns in the EEG signal to diagnose any abnormality. There were only 150 neurologists in Pakistan in 2011 according to [18]. According to this report, 33% of Pakistani population above the age of 45 years are estimated to be suffering from hypertension. Around one-third of them were unaware of their disease. Dr. Wasay, in this report, said that the burden of neurological diseases in developing countries, including Pakistan, was increasing due to rising life expectancy, urbanisation of population and better diagnostic facilities.

Mapping of EEG signals is non-trivial and replicating human analysis has a number of challenges to overcome before it is commercially accepted. EEG signals are intrinsically noisy and suffer from channel cross-talk. EEG signals not only have low signal to noise ratio but also high interpersonal variability. EEG signal varies from time-to-time depending on age, sleep-stage, medication and other unclear reasons.

Traditional EEG technology consists of bulky hardware and requires a computer for data acquisition. Moreover, signal acquisition requires application of fragile wired sensors on the scalp with the help of an elastic cap, and expert knowledge is necessary to apply EEG caps and record diagnostically useful signals.

In recent years, consumer EEG hardware has been optimized resulting in a small, wireless, head-mounted yet reasonably motion-tolerant EEG system [4], featuring very competitive signal quality [19], usable for home-based EEG acquisition [20, pp. 698-710].

Thus, there is a desperate need to provide neurological disorder management at a primary care level. Users of primary care are more likely to receive early help because of the availability of facilities, their easy accessibility, and reduced cost, thus leading to early detection of neurological disorders. As frontline caregivers, primary care providers need to receive equipment and basic training for pre-diagnosis and management of the disorder. They need to be trained to recognize the need for referral to more specialized treatment rather than trying to make a diagnosis.

High dimensionality of the data makes it computationally challenging to design an end-to-end solution. Thus, this time-consuming process must be automated to reduce the burden off of neurologists who have low inter-rater agreement as well. Hence, a platform where an EEG signal could be identified as normal or abnormal, to perform an initial screening for the neurologists is much needed. This platform would help classify streams of EEG data in real-time.

The datasets available publicly are from developed countries, with state-of-the-art equipment. Hence, there is a need for EEG datasets from developing countries like Pakistan. This would help observe the trends of neurological diseases in such countries. Hence, we are developing a low-cost EEG device which can be used to collect a curated dataset from hospitals in Pakistan, to aid the on-going research in the field of automated EEG analysis.

Thus, an easy to use, low-cost device, accompanied by an intelligent system, facilitating the diagnosis of neurological disorders, especially epilepsy, is urgently needed in Pakistan and other underdeveloped countries.

Chapter Summary

This chapter provides a comprehensive summary of the problems faced in providing quality neurological healthcare in Pakistan, particularly in rural areas. It discusses the importance of non-invasive scalp-recorded EEG in the diagnosis and monitoring of neurological diseases, the stark contrast between the treatment received by epilepsy patients in developing and developed countries, the dearth of qualified neurologists in Pakistan, and the increase in the burden of neurological disorders in developing countries. Furthermore, it discusses the problems associated with traditional EEG recording hardware, the time-consuming process of EEG interpretation and the low IRA between neurologists in EEG classification. It concludes that there is a dire need of a low-cost EEG recording device accompanied with an intelligent system which can facilitate the diagnosis of neurological disorders like epilepsy

Chapter 4

MATERIAL AND METHODS

4.1 PCB Design

EasyEDA is an open-source software by JLCPCB China. It is used to design schematics and PCB layouts for a simple 2-layer PCB to 16-layer PCB. JLCPCB is a PCB manufacturing company that not only manufactures PCB but also provides its services for PCB assembly known as SMT or Surface Mount Technology. We used this software to design our PCB because our aim was to order STM services.

Initially we designed two-layer PCB for our board, but later on to reduce noise effects Texas instruments suggested separate analog and digital grounds so we extended it to four layers. Upper layer mainly consists of power components and digital grounds while the lower layer is of analog ground. Third and fourth layers are a mixture of analog and digital grounds along with power layers such as DVDD, AVSS and AVDD.

4.2 Arduino IDE

Arduino is an open-source electronics platform based on easy-to-use hardware and software. It is very popular and provides support for a large number of microcontrollers. For our project we are using ESP32 microcontroller to communicate with all the sensors, modules and ADS1299. To program ESP32 we used Arduino IDE as it provides support for all the ESP32 series of boards with all the necessary libraries required for communication.

Arduino IDE provides tools like Serial Monitor and Serial Plotter which are very useful for debugging purposes.

4.2.1 SPI.h

SPI library provided with Arduino IDE is used for SPI communication between our microcontroller and ADS1299 and SD Card. SPI class is used to create two different instances of SPI which are used to establish two independent SPI communication channels.

4.2.2 SD.h and FS.h

SD.h and FS.h are the two libraries used for communication with SD Card. FS.h is the file system wrapper and is a part of ESP8266 core for the Arduino environment. It provides all the necessary methods to read, write, delete, rename directories and files.

4.2.3 Bluetooth Serial

The ESP32 comes with Wi-Fi, Bluetooth Low Energy and Bluetooth Classic. For our project we are using Bluetooth classic with Arduino IDE to exchange data between ESP32 and Smartphone. Bluetooth Classic is simpler than Bluetooth low energy and uses Arduino's standard serial protocol and functions.

BluetoothSerial.h library provides us a Bluetooth Serial class which allows us to use the inbuilt Bluetooth of ESP32. We can control all the Bluetooth parameters using this library.

4.2.4 Wire.h

This library allows you to communicate with I2C / TWI devices. We are using an accelerometer to record head movements which communicate using I2C protocol. To get the data from an accelerometer we are using the Wire library provided with Arduino IDE.

4.3 EEG Acquisition

The EEG is recorded with the help of an EEG headset which consists of small metal discs usually made of stainless steel, tin, gold, or silver covered with a silver chloride coating. These discs are placed on the scalp as nodes in special positions. These positions are officially specified using the International 10-20 system [21, pp. 370-375]. The placement of electrodes on the head is referred to as a montage. These montages define the signal between two electrodes by subtracting the adjacent channels. This gives the electrical signal residing between the two points. However, artifacts may be introduced by jaw movement such as chewing, or head bobbing. Each electrode location is labeled with a letter and a number. The letter refers to the area of the brain underlying the electrode e.g. Fp denotes Prefrontal lobe, F denotes Frontal lobe, T denotes Temporal lobe, C denotes Central lobe, P denotes Parietal lobe, O denotes Occipital lobe, and A denotes Mastoid Process lobe. Similarly, even numbers denote the right side of the head and odd numbers the left side of the head. Figure 2 shows the international 10-20 system of electrode placement.

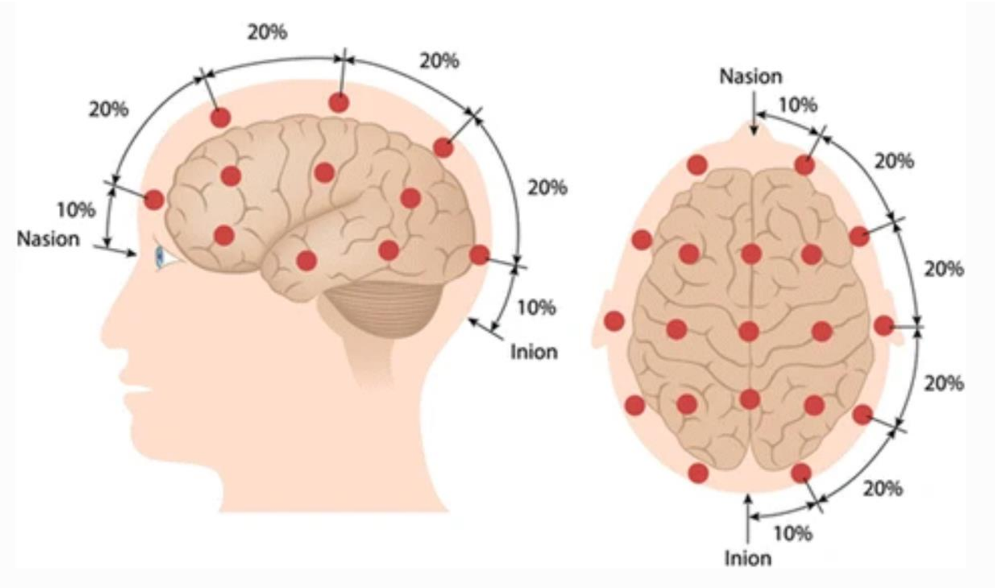

Figure 2: The international 10–20 system. The left image shows the left side of the head, and the right image presents the view from above the head [22]

4.4 Signal Pre-processing

Raw EEG signals are contaminated with a lot of noise such as power line interference, muscle movement and eye blinks. The presence of this noise can mask the EEG data which is of low amplitude and may affect the analysis of the data. Therefore, it is important to remove these types of noise via filtering in order to get a clear signal which is diagnostically useful. However, excessive filtering may result in signal distortion and loss of data [23, pp. 280-293]. Therefore, it is necessary to find a balance between the amount of filtering done and the acceptable noise threshold. A typical pipeline of the process of filtering from measuring the EEG signals to displaying them is shown in Figure 3.

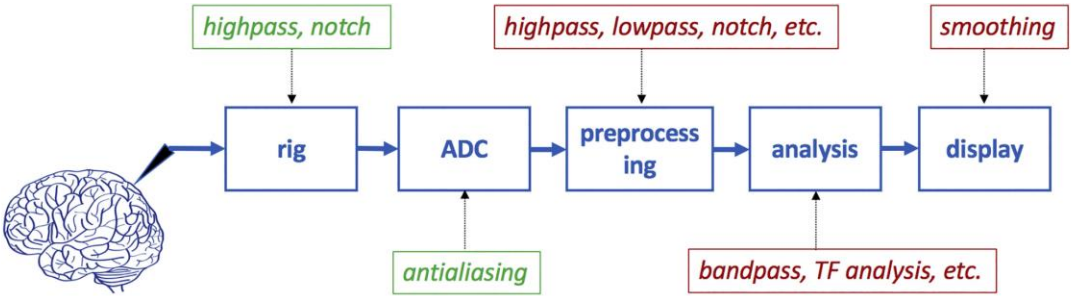

Figure 3: A Typical Recording-to-Publication Data Pipeline, Showing Where Filters Are Applied [23]

Infinite Impulse Response (IIR) filters are recursive filters which use current inputs, previous inputs, previous outputs to compute the output. Because the filter uses previous values of the output, there is feedback of the output in the filter. The design of the IIR filter is based on identifying the pulse transfer function G(z) that satisfies the requirements of the filter specification [24]. Butterworth filters are a type of IIR filters which provide a maximally flat passband. The reason for this to have uniform sensitivity for all the frequencies in the passband. Butterworth filters are commonly used to remove noise in physiological signals [25].

The majority of useful information about the brain's functional state lies in five frequency bands. The waves belonging to different bands are distinguished through their frequency ranges. These frequency bands are delta band (0–4 Hz), theta band (3.5–7.5 Hz), alpha band (7.5–13 Hz), beta band (13–26 Hz), and gamma band (26–70 Hz) [26]. Delta waves are related to the deep sleep state. Theta waves are related to the deepest state of mediation. Alpha waves are related to the case of dreaming and relaxation. Beta waves are the dominant with the waking state with large attention. Gamma waves are highly related to decision-making. When dealing with mental illnesses states, unexpected disturbances of the brain waves occur leading to the need of considerable signal processing burdens for diagnosis of abnormal states [26].

Since the majority of meaningful EEG data is within 5-55 Hz, we have used a Butterworth bandpass filter of order 5 which is centered at 30Hz with a passband of 50Hz. This removes high frequency noise that frequently contaminates EEG signals. Another source of noise in EEG data is the electrical line power interference which is most commonly 50Hz or 60Hz depending on the country. For Pakistan, the frequency of AC current is 50Hz. In order to remove this frequency, a notch filter of order 2 is used at 50Hz during the preprocessing stage. Figure 4 shows our successive application of the bandpass and the notch filter applied to data of eye blinks collected from the EEG device.

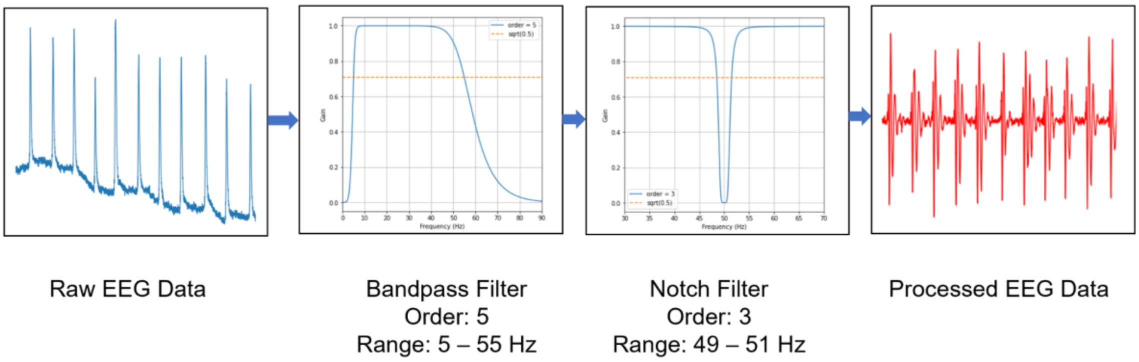

Figure 4: Butterworth bandpass and notch filter applied successively to raw data of eye blinks

4.5 Dear ImGUI

The data is visualized using a C++ library called Dear Imgui which is known for it\s bloat free nature. The library was selected on account of it running faster due to its C++ implementation. For our application, several graphs are plotted concurrently in the GUI which show the real-time data from the eight EEG channels, the status of the electrode connectivity, the Fourier transforms of the EEG channels, the magnitude of the alpha waves being generated by the user and the accelerometer data. The user has the option to select which channels they want to focus on, and which features they want to toggle on and off.

Chapter Summary

This chapter provides a comprehensive summary of the methods, tools and techniques used in designing the custom PCB for data acquisition, the libraries to configure additional features like the SD card, accelerometer and Bluetooth connectivity, the SPI communication between the PCB and the microcontroller, and the project's GUI. It presents an overview of the international 10-20 system of electrodes placement used and describes the filters used to remove noise in the raw EEG data.

Chapter 5

DESIGN AND ARCHITECTURE

5.1 SYSTEM ARCHITECTURE

The modular EEG design consists of the ADS1299 ADC chip by Texas Instruments, the power up circuit for ADS1299, noise reduction circuitry, and a microcontroller to communicate with ADS1299. The ADS1299 module takes EEG signals which are passed through RC noise reduction circuitry before reaching the microcontroller. SPI communication is used to communicate between ADS1299 and the microcontroller. Once the signal is attained it is then processed on Esp32 for noise reduction. A notch filter at 50Hz is used to remove electrical AC noise from the EEG signal. The signal is then passed through a Butterworth filter of 5-55 Hz to remove the higher and lower frequency components which are also considered as noise. An accelerometer is used to collect data about head movement. The skin-electrode impedance is also calculated in order to determine if the electrodes are connected firmly. Finally, the EEG signals, the accelerometer data and the impedance is sent via Bluetooth to a PC for visualisation and further processing.

5.1.1 Architecture Design

Figure 5 shows the data flow diagram used in the design approach of our project:

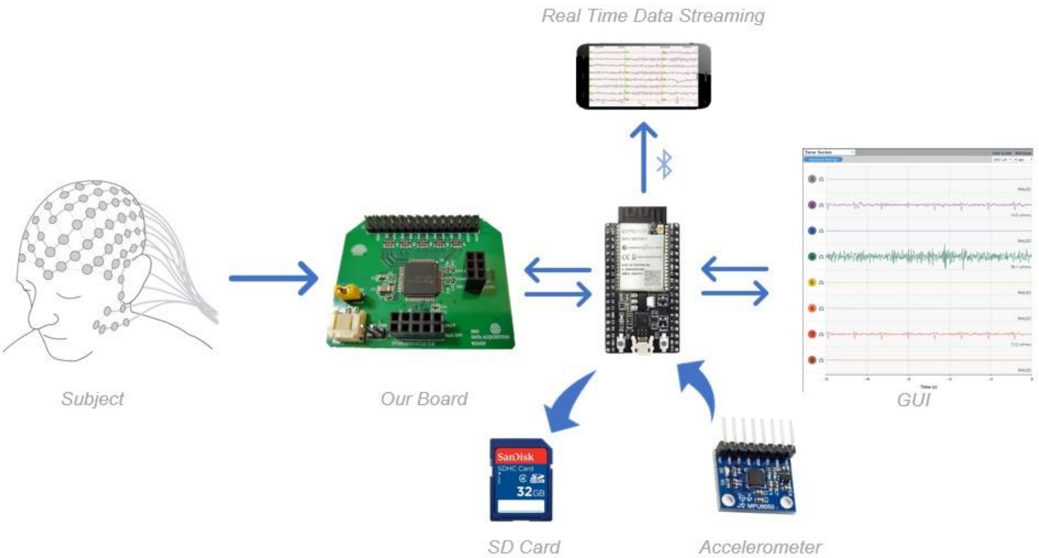

Figure 5: Data Flow Diagram

5.2 DETAILED SYSTEM DESIGN

5.2.1 ADS1299 by Texas Instrument

Texas Instruments ADS1299 is a system on chip (SOC) specifically designed for biopotential applications including electroencephalography (EEG) and electrocardiography (ECG). It has attractive electrical characteristics such as low input referred noise (1 μV_{pp}), low power consumption (5 mW/channel), test signals for impedance measurement, and an SPI compatible interface [6]. As discussed above, it has attracted considerable attention from the biomedical research community, both for clinical research and the development of mobile brain computer interfaces (BCIs).

These characteristics of ADS1299 motivated us to use it as an ADC in our final year project to make a cost effective and portable EEG device that can be used to monitor EEG signals for medical use and Brain Computer Interface (BCI) operations.

5.2.2 Features

With up to eight low-noise programmable-gain amplifiers (PGAs) and eight high resolution simultaneous-sampling ADCs, theADS1299 is a suitable choice for the acquisition of physiological signals like EEG, ECG and EMG [6]. Some distinctive features of ADS1299 amongst other ADCs are provided in table IV.

Table IV: Distinctive Features of ADS1299 by Texas Instruments

No. of ADCs	Up to 8
Input referred noise	1 μVPP (70-Hz BW)
Input bias current	300pA
Data rate	250sps - 16ksps
CMRR	-110dB
Programmable gain	1, 2, 4, 6, 8, 12, or 24
Power Supply	Unipolar or bipolar – Analog: 4.75 V to 5.25 V – Digital: 1.8 V to 3.6 V
Lead-off detection	Built- in
Oscillator	Built -in
Reference	Internal or External
SPI compatibility	Yes
Operating temperature range	–40°C to +85°C

5.2.3 Description

The ADS1299 device is a 24-bit, simultaneous-sampling delta-sigma (ΔΣ) analog-to-digital converter (ADC) with a built-in programmable gain amplifier (PGA), internal reference, and an onboard oscillator. The ADS1299 incorporates all commonly-required features for extracranial electroencephalogram (EEG) and electrocardiography (ECG) applications. With its high levels of integration and exceptional performance, the ADS1299 enables the creation of scalable medical instrumentation systems at significantly reduced size, power, and overall cost [6]. The block diagram of the ADS1299 is shown in Figure 6.

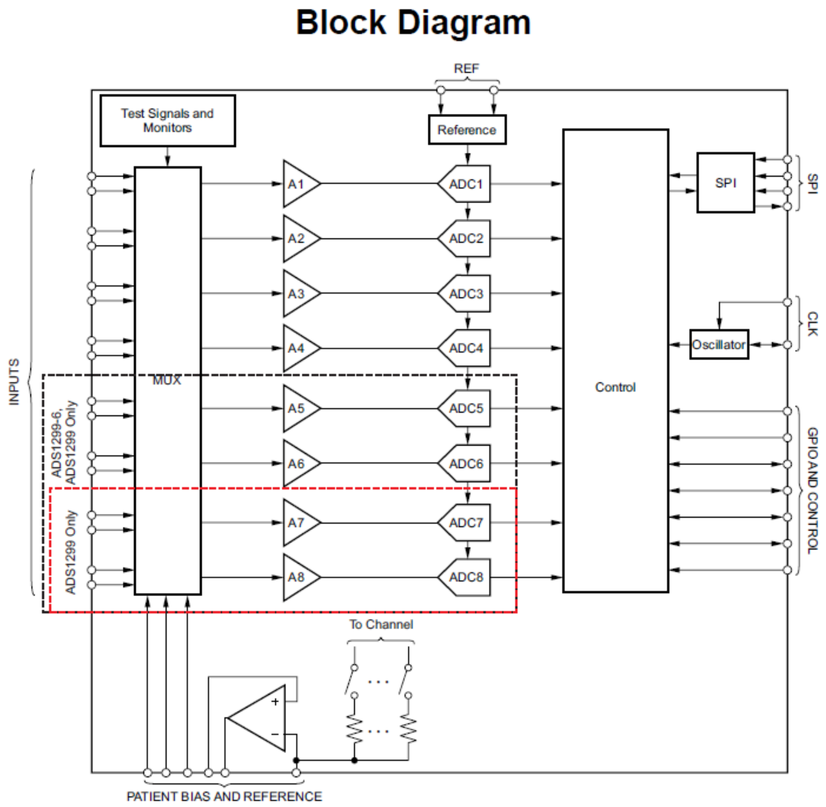

Figure 6: Block Diagram of ADS1299 [6]

The ADS1299 has a flexible input multiplexer per channel that can be independently connected to the internally-generated signals for test, temperature, and lead-off detection. Additionally, any configuration of input channels can be selected for derivation of the patient bias output signal. Optional SRB pins are available to route a common signal to multiple inputs for a referential montage configuration. The ADS1299 operates at data rates from 250 SPS to 16 kSPS. Lead-off detection can be implemented internal to the device using an excitation current sink or source. Multiple ADS1299 devices can be cascaded in high channel count systems in a daisy-chain configuration.

5.2.4 Daisy chain mode

Daisy chain mode allows us to expand the number of input channels by daisy chaining 2 ADS1299 boards so that we have a total of 16 input channels. Board we designed for ADS1299 is compatible with daisy chain configuration. We have provided external headers for daisy-in pin, start pin and clock pin of ads1299 which are used for daisy chain configuration as shown in Figure 7.

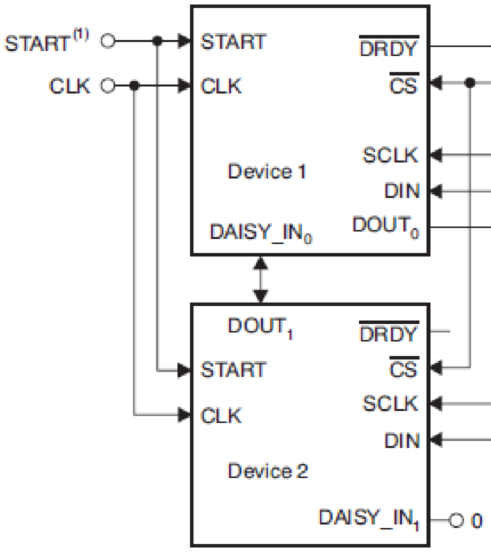

Figure 7: Daisy Chain Configuration [6]

5.2.5 Powering method used for ADS1299

The input power to the ADS1299 is passed through a 3.3V voltage regulator that provides main power to the chip. The ADS1299 provides two power up methods for its internal amplifiers, namely *Unipolar supply* and *Bipolar supply*.

a) Unipolar supplies

Powering up ADS299 using unipolar supplies allows it to acquire only positive signals as an input from all channels. To connect ADS1299 in this mode, it is necessary to provide +5V to AVDD pins and connect AVSS pins to ground as shown in figure 8.

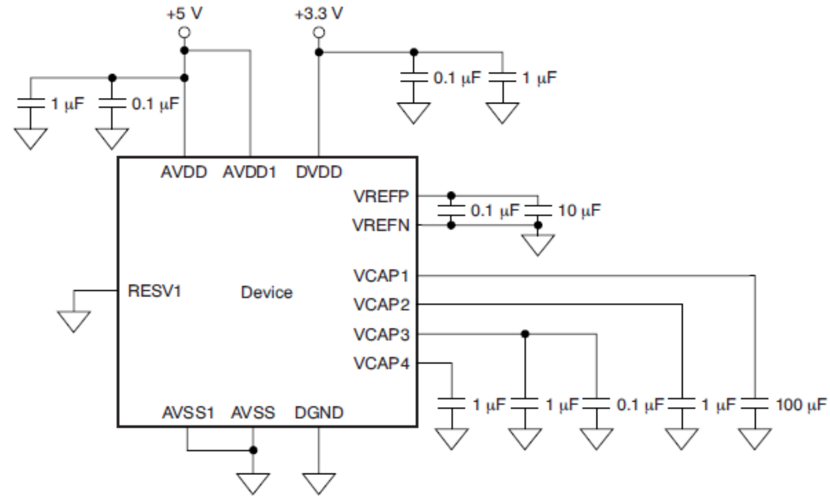

Figure 8: Unipolar power supply configuration [6]

b) Bipolar supplies

Powering up ADS299 using bipolar supplies allows it to acquire both positive and negative signals as an input from all channels. To connect ADS1299 in this mode, it is necessary to provide +2.5V to AVDD pins and -2.5V to AVSS pins.

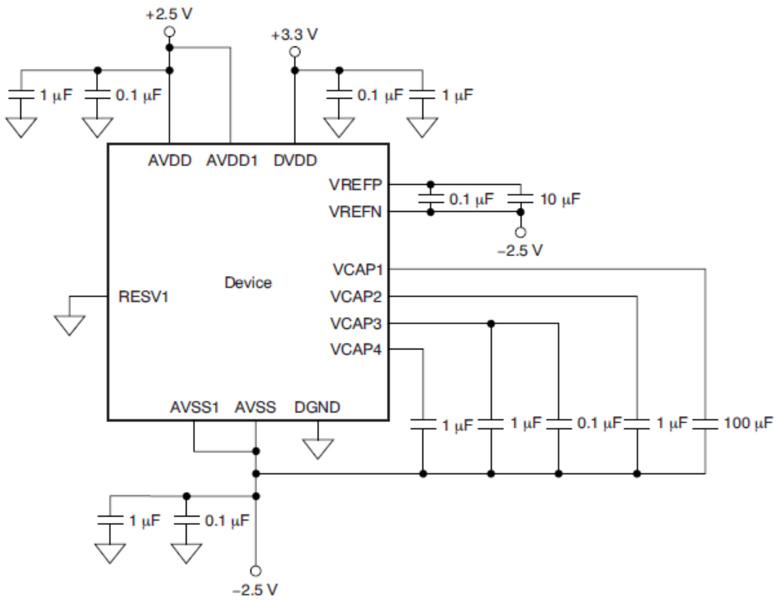

Figure 9: Bipolar Supply Configuration [6]

In this project we opted for bipolar mode for powering ADS1299 so that it is possible to acquire both polarities of an EEG signal. Noise can also be removed more efficiently in bipolar mode. Thus, using Bipolar mode, we achieved a balance between system performance, noise cancellation and power efficiency.

5.2.6 PCB Design

Designing the PCB to power up the ADS1299ADI and to conduct SPI communication with least possible noise interference was a challenging task. The software we used for PCB design was EasyEDA by JLCPCB. The reason we used this software was because we can directly order our PCB from JLCPCB within the software.

TI recommends employing best design practices when laying out a printed-circuit board (PCB) for both analog and digital components. This recommendation generally means that the layout separates analog components such as ADCs and amplifier from digital components such as digital power up systems to power up ADS1299 (i.e., 3.3v, +2.5v and -2.5v power supplies) and microcontrollers to reduce the noise interference.

Figure 10 outlines some basic recommendations for the layout of the ADS1299 by Texas Instruments.

• Separate analog and digital signals. To start, partition the board into analog and digital sections where the layout permits. Route digital lines away from analog lines. This configuration prevents digital noise from coupling back into analog signals.

• The ground plane can be split into an analog plane (AGND) and digital plane (DGND), but is not necessary. Place digital signals over the digital plane, and analog signals over the analog plane. As a final step in the layout, the split between the analog and digital grounds must be connected together at the ADC.

• Fill void areas on signal layers with ground fill.

• Provide good ground return paths. Signal return currents flow on the path of least impedance. If the ground plane is cut or has other traces that block the current from flowing right next to the signal trace, then the current must find another path to return to the source and complete the circuit. If current is forced into a longer path, the chances that the signal radiates increases. Sensitive signals are more susceptible to EMI interference.

• Use bypass capacitors on supplies to reduce high-frequency noise. Do not place vias between bypass capacitors and the active device. Placing the bypass capacitors on the same layer as close to the active device yields the best results.

• Analog inputs with differential connections must have a capacitor placed differentially across the inputs. The differential capacitors must be of high quality.

Figure 10: Recommendations for the design of PCBs incorporating ADS1299 [6]

We kept these instructions in mind while making schematics and PCB for our custom ADS1299 board in order to lower the electromagnetic interference (EMI) and hence reduce the noise in the captured EEG signals.

5.2.7 Schematics

Schematics were drawn in EasyEDA's schematic editor while keeping in mind the recommendations by TI. In this regard, we separated analog and digital signals. Analog signals include all the inputs from the 8 channels and their noise reduction RC circuits containing resistor and capacitor boxes. Digital signals include bipolar supplies and regulators, namely +2.5V and -2.5V voltage regulators, 3.3V power source and external SPI communication pins. Important sub modules in the schematics are described in the upcoming sections.

a) Power supplies

The **power** supplies are regulated using four voltage regulators namely MCP1754T for 3.3v, LM2644 for inverting 3.3V, TPS72325DBVR which takes input from LM2644 and outputs -2.5V, TLV70025QDDCRQ1 which also takes input from LM2644 and outputs +2.5V. We also used a Schottky diode at the input to avoid any back currents. Fig 11 shows the connections of all these components.

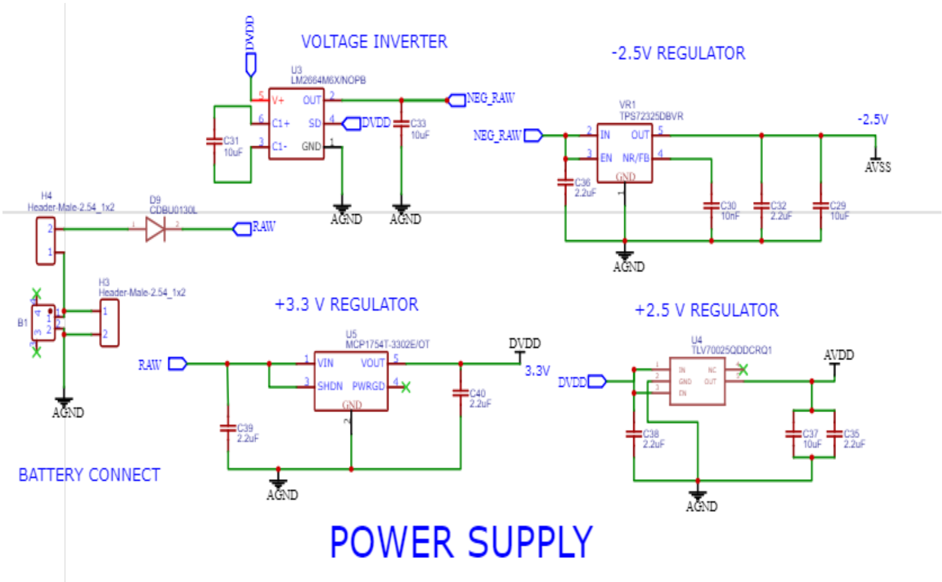

Figure 11: Schematic of power supply

b) Input Signals

The input signals consist of 8 channel input electrodes, BIAS and a reference electrode. All these inputs are first passed through the TPD4E1B06DCKR module which is a 4-channel bi-directional Transient Voltage Suppressor (TVS) diode array. This device features ultra-low leakage current (0.5 nA) for precision analog measurements. After this these signals are fed into resistor arrays of resistance 2.2 kΩ, namely CAY16-2201F4LF, which is further connected to a capacitor array of 1000pF namely, CKCL44X7R1H102M085AA. This configuration forms an RC circuit which helps to reduce noise in input signals. Figure 12 shows one part of this whole circuitry.

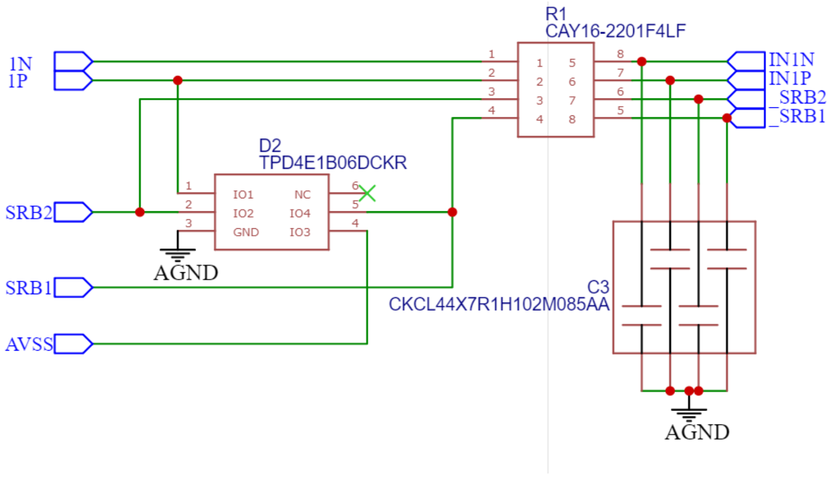

Figure 12: A section of the schematic for the custom PCB

c) ADS Decoupling

Decoupling capacitors are used in abundance with input power sources to ensure a pure DC input power signal to power up the ADS1299 chip. Capacitors used for this purpose are Multilayer Ceramic Capacitors MLCC- SMD/SMT of values 100nF and 1uF. These capacitors have a rated voltage of 16V with tolerance of 10%. Package we used for this purpose is 0402. Figure 13 shows the circuitry of the decoupling circuit.

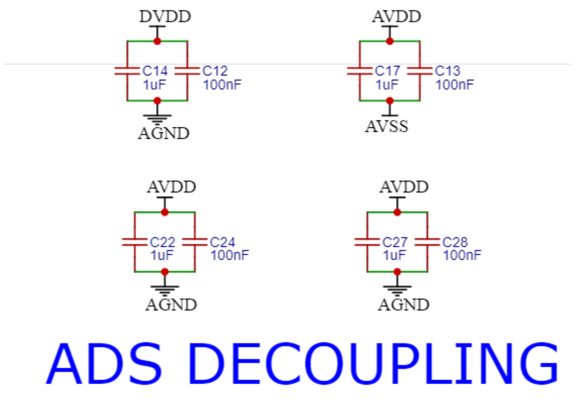

Figure 13: The circuitry used to decouple the ADS1299

5.2.8 PCB

The PCB was designed using EasyEDA software. We made a four-layer printed circuit board to separate the analog and digital grounds in order to reduce the effect of noise. The topmost layer of the PCB mainly consists of digital signals like power sources and SPI communication traces. ADS1299, the heart of the board, is on the topmost layer along with resistor boxes of RC circuits. Female pin headers of pitch 2.54mm are used for external connection to provide a rigid contact. The physical specifications of this custom PCB are detailed in Table V. The sEEGs PCB is shown in Figure 14.

Table V: Physical Characteristics of Custom PCB

Dimensions	50x41mm
Layers	4
Number of SMD Components	54
No. of through hole components	5
Board type	Single piece
Material	FR-4
Thickness	1.6mm
Minimum track spacing	6/6 mil
Minimum hole size	0.3mm
Surface finish	HASL with lead
Finished Copper	1 oz Cu.

Figure 14: The custom sEEGs PCB designed for EEG data acquisition

Chapter Summary

This chapter provides a detailed overview of the system design of the custom PCB and how various functionalities were partitioned into different layers of the printed circuit board. It discusses the different subsystems in the PCB like the ADS1299, the power up circuit, the power supply regulation system, and the decoupling system. For each subsystem, the functionality, constraints, and responsibilities in the overall system are discussed.

Chapter 6

IMPLEMENTATION

6.1 Interfacing ADS1299 with ESP32

Interfacing of our custom designed ADS1299 based data acquisition board with our microcontroller ESP32 is done using Arduino IDE. Arduino IDE provides a way to program ESP boards using the boards manager. We choose ESP32 over other alternatives because it is a low-cost SOC with integrated Wi-Fi and dual-mode Bluetooth. It runs on a 32-bit Tensilica Xtensa LX6 microprocessor @ 160 or 240 MHz. It provides all the necessary communication protocols that we need in a single package.

6.1.1 Hardware Configuration

The ADC used in our project is ADS1299 from Texas Instruments that communicates with our microcontroller using SPI protocol. SPI runs at a master clock speed of 4 MHz.

ESP32 integrates 4 SPI peripherals. SPI0 and SPI1 are used internally to access the ESP32's attached flash memory. SPI2 and SPI3 are general purpose SPI controllers, sometimes referred to as HSPI and VSPI, respectively. They are open to users. SPI2 and SPI3 have independent bus signals with the same respective names. Each bus has three CS lines to drive up to the same number of SPI slaves. To establish successful communication with our ADC we need to use either SPI2 or SPI3 alternatively HSPI or VSPI. We have used HSPI. Pin connection of the ESP32 with our ADC is given in Table VI.

Table VI: ESP32 and ADS1299 Pin Configuration

ESP32	**ADS1299**
D14	SCLK
D12	DOUT
D13	DIN
D15	SS
D32	RESET
D33	DRDY

6.1.2 Software Configuration

The ADS1299 provides flexible configuration control. The commands, summarized in Table VII, control and configure device operation. The commands are stand-alone, except for the register read and write operations that require a second command byte plus data.

Table VII: SPI Commands for ADS1299 [6]

COMMAND	DESCRIPTION	FIRST BYTE	SECOND BYTE
System Commands			
WAKEUP	Wake-up from standby mode	0000 0010 (02h)	
STANDBY	Enter standby mode	0000 0100 (04h)	
RESET	Reset the device	0000 0110 (06h)	
START	Start and restart (synchronize) conversions	0000 1000 (08h)	
STOP	Stop conversion	0000 1010 (0Ah)	
Data Read Commands			
RDATAC	Enable Read Data Continuous mode. This mode is the default mode at power-up.(1)	0001 0000 (10h)	
SDATAC	Stop Read Data Continuously mode	0001 0001 (11h)	
RDATA	Read data by command; supports multiple read back.	0001 0010 (12h)	
Register Read Commands			
RREG	Read *n nnnn* registers starting at address *r rrrr*	001*r rrrr* (2xh)(2)	000*n nnnn*(2)
WREG	Write *n nnnn* registers starting at address *r rrrr*	010*r rrrr* (4xh)(2)	000*n nnnn*(2)

(1) When in RDATAC mode, the RREG command is ignored.
(2) *n nnnn* = number of registers to be read or written – 1. For example, to read or write three registers, set *n nnnn* = 0 (0010). *r rrrr* = starting register address for read or write commands.

SPI of ESP32 is programmed using the SPI class provided with the Arduino IDE for AVR microcontrollers. Sample Code for the start command is mentioned below.

```
#define _START 0x08
void start()
{
  digitalWrite(CS,LOW);
  delayMicroseconds(3);
  hspi->transfer(_START);
  digitalWrite(CS,HIGH);
  delayMicroseconds(3);
}
```

All the other commands are implemented using the same procedure.

6.2 Lead-off Detection

Patient electrode impedances are known to decay over time. These electrode connections must be continuously monitored to verify that a suitable connection is present. The ADS1299 lead-off detection functional block provides significant flexibility to the user to choose from various lead-off detection strategies. Though called leadoff detection, this is in fact an electrode-off detection.

The basic principle is to inject an excitation current and measure the voltage to determine if the electrode is off. ADS1299 provides us two options for this purpose, DC lead off and AC lead off. We opted for AC lead off detection because it gives us analog outputs instead of DC lead off which gives us binary outputs

In this method, an in-band ac signal is used for excitation. The ac signal is generated by alternatively providing a current source and sink at the input with a fixed frequency. The frequency can be chosen by the FLEAD_OFF[1:0] bits in the LOFF register. The excitation frequency is chosen to be one of the two in-band frequency selections (7.8 Hz or 31.2 Hz). We opted for 31.2Hz. The magnitude of the current can be set to 6nA, 24nA, 6uA or 24uA by using the ILEAD_OFF[1:0] bits in the LOFF register, we opted for 6uA. Code for lead off detection is below

```
wreg(LOFF,0x0A); //0000 1010  31.2 Hz, 6uA
wreg(LOFF_SENSN, 0XFF); //All N channels are on for AC lead
off
```

6.3 Bluetooth Communication

Eight Channel raw data along with status registers, accelerometer data and skin-electrode impedance can be transmitted via Bluetooth to any device. ESP32 comes with Bluetooth Classic and Bluetooth Low Energy (BLE). For our project we are using Bluetooth Classic as we will stream the data continuously from the device. Bluetooth configuration in ESP32 is straightforward. *BluetoothSerial* class will provide us all the methods required for Bluetooth communication. Bluetooth communication will take place at Baud of 115200. Sample Code for Bluetooth read and write is provided below:

```
BluetoothSerial SerialBT;

if (Serial.available())
     SerialBT.write(Serial.read());


if (SerialBT.available())
  Serial.write(SerialBT.read());
```

6.4 SD Card Storage

For local storage of the raw data, we are using SD card. The communication between the ESP32 and SD Card uses standard SPI interfaces. This bus type supports only 3.3V interfaces.

6.4.1 Hardware Configuration

SD Card interfacing can be done using an SD Card adapter or SD Card Module. SD card adapter works on 3.3V voltage level thus eliminating the need of 5V power supply as ESP32 also works on 3.3V voltage level, but for secure data transmission it is recommended to use 5V SD Card module. Wiring of the SD Card Module with ESP32 is similar to any other SPI device.

For SD Card communication we are using VSPI/SPI3 provided by ESP32. Pin connections of ESP32 with micro–SD Card Module is given in Table VIII.

Table VIII: ESP32 and MicroSD card module Pin Configuration

ESP32	**Micro SD Card Module**
D18	SCLK
D19	MISO
D23	MOSI
D5	CS
3V3	VCC

GND	GND

6.4.2 Software Configuration

The SD card library provided with the ESP32 supports both FAT32 and FAT16 file systems. This library provides all the necessary functions required for reading, writing and storage information. For our project we only need a write function which appends the raw data to the file.

Including SD.h automatically creates a global "SD" object which can be interacted with in a similar manner to other standard global objects like "Serial". When writing to the SD Card we will be writing using a buffer which writes 2000 32-bit samples (250 samples from 8 channels) at an instance. In this way the overall performance of the system improves significantly. Sample function of the SD Card write is provided below.

```
void sdwrite(fs::FS &fs, const char * path)
{
    File file = fs.open(path, FILE_APPEND);
    if(!file)  return;
    for (size_t i = 0; i < 2000; i++)
    {
      file.print(buff[i]);
      if((i+1) % 8 == 0) file.print("\n");
      else  file.print(",");
    }
    file.print("\n\n");
    file.close();
}
```

6.5 Accelerometer

Interfacing of the 3-axis accelerometer is also done in the overall package. It could be used to sense orientation (or change in orientation) of the head as part of BCI. Or, it can be used to sense rough motion, which might suggest any motion artifacts in the EEG data. Another possible use is tapping on the board as a way to introduce markers during data collection.

6.5.1 Hardware Configuration

To implement the 3-axis accelerometer we need a separate module for that purpose. We are using GY-521 which is a breakout board for MPU-6050 MEMS (Microelectromechanical systems) sensor that features a 3-axis gyroscope, a 3-axis accelerometer, a digital motion processor (DMP), and a temperature sensor. The digital motion processor can be used to process complex algorithms directly on the board. Communication between GY-521 and ESP32 is done using I2C (inter-integrated circuit) protocol. Pin connections of ESP32 with GY-521 Module are given in Table IX.

Table IX: ESP32 and GY-521 Pin Configuration

ESP32	**GY-521**
D22	SCL
D21	SDA
3V3	VCC
GND	GND

6.5.2 Software Configuration

For I2C communication, Arduino provides a 'Wire.h' library. In I2C protocol Master device requires address of slave device to begin transmission. The slave address can be found in the datasheet of the sensor or it can be found using a loop with addresses ranging from 0-127 or 0-255 and waiting for the return signal. MPU-6050 Address is 0x68. Sensor's default setting is deep sleep mode, so it needs to exit from sleep mode. It can be done by writing 0 to the PWR_MGMT_1 register of the sensor whose location is 0x6B. 3-axis data of the accelerometer is found at the register location of 0x3B. Sample code for collecting the 16-bit 3-axis (6 bytes) data is given below

```
// Setup
```

```
Wire.begin();
Wire.beginTransmission(0x68);
Wire.write(0x6B); //PWR_MGMT_1 Register
Wire.write(0); // Wakes up
Wire.endTransmission(true);

// Loop
Wire.beginTransmission(0x68);
Wire.write(0x3B);
Wire.endTransmission(false);
Wire.requestFrom(0x68, 6, true); // Reading 6 cont. bytes
accelerometer_x = Wire.read()<<8 | Wire.read();
accelerometer_y = Wire.read()<<8 | Wire.read();
accelerometer_z = Wire.read()<<8 | Wire.read();
```

6.5 Graphical User Interface

In order to facilitate the real-time visualization of the EEG recordings collected from the device, we have developed a GUI. This will be used to display the data being received from the sEEGs device which includes the eight channel EEG data, the accelerometer data, and the electrode-skin impedance data. Furthermore, it will process the EEG data in order to display further graphs including the Fourier transforms and the concentration level of the user for further analysis. The users will be able to control which electrode data they wish to view, and which filters they wish to apply through the GUI. As these are a lot of processes to be carried out concurrently, multithreading is used so that the real-time streaming of the data is not inversely affected.

6.5.1 Reading Serial Data

The data is being streamed serially via Bluetooth and the serial port is being continuously read. The EEG data is sent sequentially from channel 0 to channel 8 at the rate of 250 samples per seconds. The accelerometer data and the impedance data is sent at a lower rate. Error prevention mechanisms are in place to prevent the channel data from getting jumbled up if a single reading is missed. Therefore, the function waits for 8 readings to be collected before moving on to the next set of readings. This process of reading the serial port is carried out on a separate thread so that it is not slowed down by the functions involved in processing the data and those involved in updating the graphs.

6.5.2 Data Processing

Raw EEG data needs signal processing before it can be used for analysis. A Butterworth bandpass filter (5-55 Hz) and a notch filter (50 Hz) are used in order to filter this data and remove the low and high frequencies which add noise to the signal as well as the AC electricity interference. The GUI presents the user the option to select which combination of these filters they wish to apply on the raw data before visualization. The possible filter combinations that can be selected by the user are no filters, bandpass filter only, notch filter only, and both bandpass and notch filter.

The Fourier transforms of EEG signals provide additional insight about the nature of the electrical activity in the brain and are diagnostically useful. They have also been found to be useful for neural networks in automatic diagnosis of EEG. Therefore, the Fourier transform of the EEG data is also calculated and visualised in the GUI.

Alpha waves are electrical brain signals in the range of 8-12 Hz and are a measure of wakeful rest. While concentrating on a task, the magnitude of alpha waves tends to decrease whereas it increases while a person is relaxing. In order to separate the alpha waves component of the EEG data, we apply a bandpass filter with a narrow passband, centered at 10Hz. Further data is collected at the guard frequencies near 10 Hz. The difference between these two signals is calculated to be an approximation of the magnitude of the alpha wave’s component in the brain signal and is also computed. This is used as an indication of the concentration level of the user.

6.5.3 Data Visualization

The data is visualized using a C++ library called Dear Imgui. Several graphs are plotted concurrently in the GUI which show the real-time data from the eight EEG channels, the status of the electrode connectivity, the Fourier transforms of the EEG channels, the magnitude of the alpha waves being generated by the user and the accelerometer data. The user has the option to select which channels they want to focus on and which features they want to toggle on and off. Since updating the graphs constantly involves a lot of processing power, this operation is done on a separate thread so it does not affect the performance of the function which is reading the data from the serial port. Figure 15 shows the layout of the GUI.

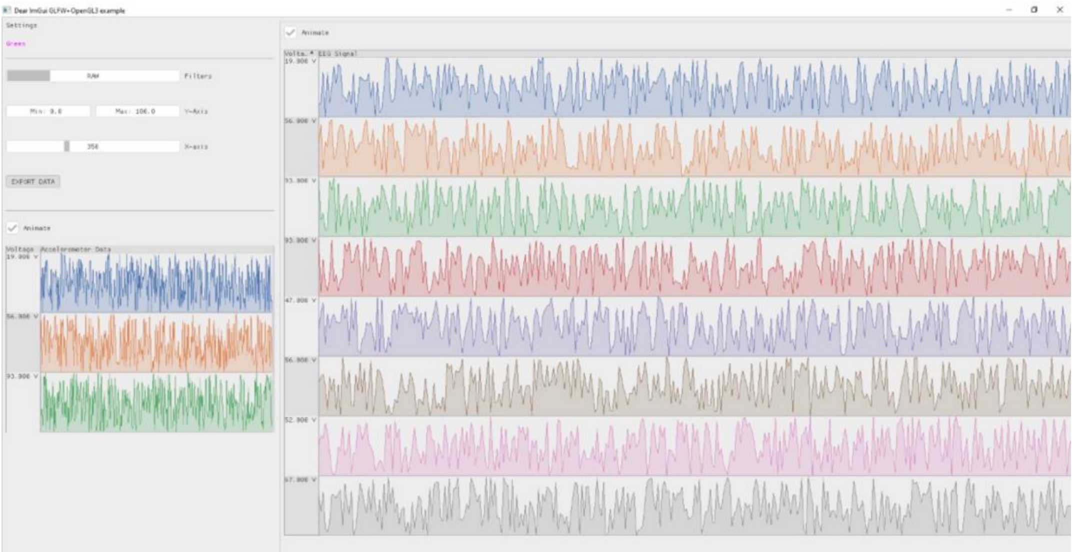

Figure 15: Custom Graphical User Interface

Chapter Summary

This chapter provides a detailed description of the implementation of all the submodules of our project. It discusses the hardware and software configurations for the ADS1299, Bluetooth, lead-off detection and accelerometer. It discusses the connectivity of these modules with the ESP32 microcontroller and provides walkthroughs for the essential code for interfacing the modules. Finally, it discusses the features of the custom GUI we have developed for our device.

Chapter 7

RESULTS AND DISCUSSION

7.1 Data Validation

The correct working of the sEEGs device was validated by giving the device waveforms of different frequencies and amplitudes as input. The measurements were read from the serial monitor in the Arduino IDE. The conversion from 24-bit digital code from ADS1299 to the required voltage values was done using the following equation:

$$\text{Scale Factor (Volts/Count)} = (4.5 \text{ Volts} / \text{Gain}) / (2^{23} - 1)$$

Figure 16 shows the generation of a 1.0V peak to peak voltage from the function generator(center) and reading it using the ADS1299 board(left). Distinct readings for this experiment are also shown (right).

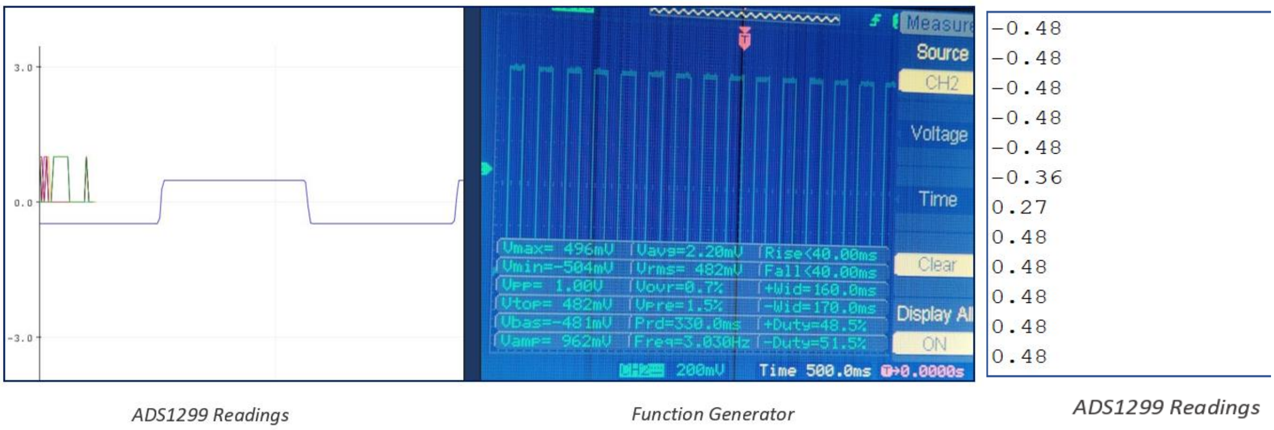

Figure 16 Data Validation

7.2 Eye Blink Signal

After the validation from the signals from the function generator. An EMG signal of jaw clench and eye blink was recorded using electrodes placed on the O1 location with Bias and Reference electrodes according to 10-20 systems of arrangement. These signals were observed with a sharp change in amplitude of the recorded signal. The signal was verified when compared to the signal acquired using OpenBCI Cyton board. Figure 17 shows the acquisition of the eyeblink data along with various stages of the filtering process i.e., the signal after being passed through a notch filter at 50 Hz and the signal after being passed through both a Butterworth bandpass filter of 5-55 Hz and a notch filter at 50 Hz.

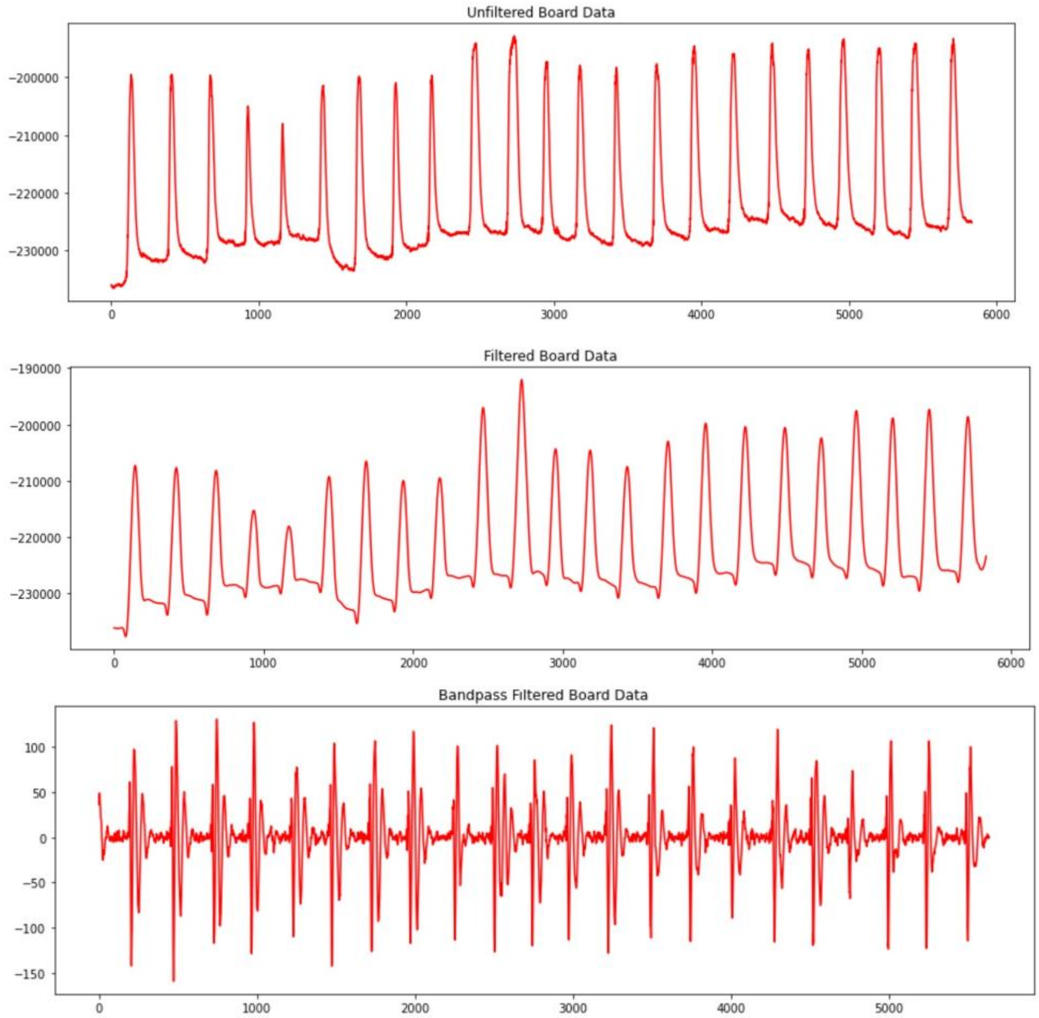

Figure 17: Unfiltered eye blink signals (top); Notch filtered eye blinks (center); bandpass and notch filtered(bottom).

7.3 Alpha waves

Alpha waves are macroscopic neural oscillations in the frequency range of 8–12 Hz. The waves simply indicate that you are in a state of wakeful rest. Alpha Waves production can be increased by stopping focusing or concentrating on a task, and simply trying to relax and unwind. Figure 18 shows alpha waves obtained using our hardware and figure 19 shows the FFT of the recorded alpha waves.

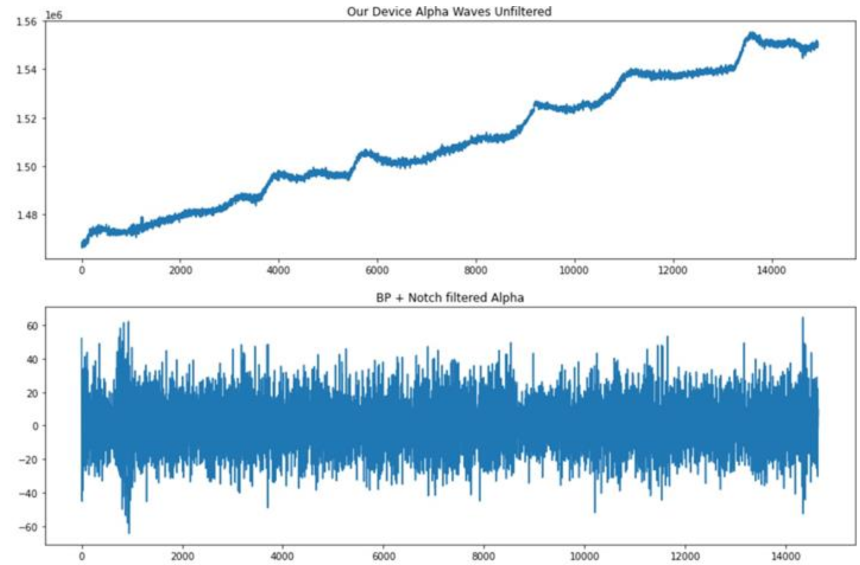

Figure 18: Raw Data (up) Filtered Data (down)

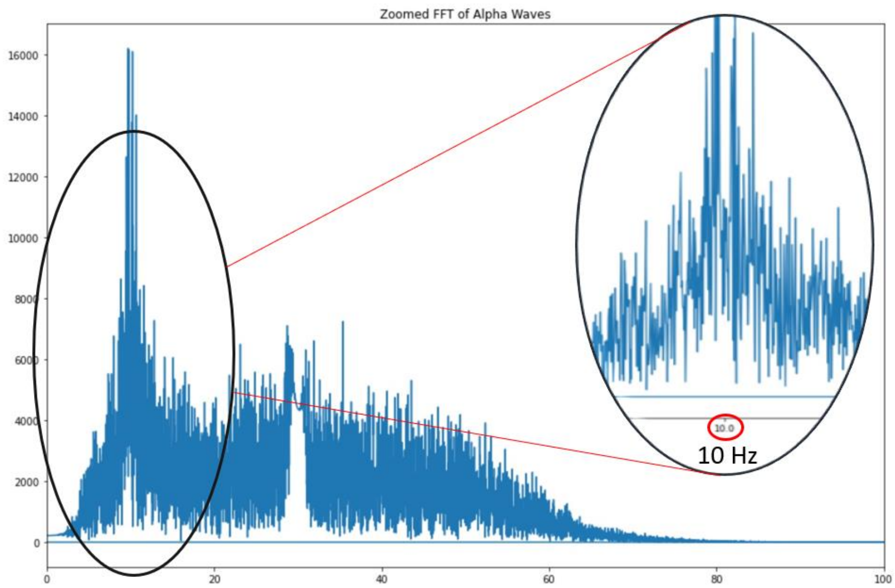

Figure 19: FFT of EEG recording of a resting subject using sEEGs which shows high activity around 10 Hz indicating presence of alpha waves.

From Fig 19, it can be seen that the signal has a component with large magnitude at 10 Hz while resting. This corresponds to the alpha waves frequency band and validates the working of the sEEGs device.

7.4 Electrode impedance

An important driver of EEG signal quality is how well the electrodes are electrically connected to the skin, also known as Lead-off detection. Common clinical and research guidance often says to use skin cleansing and skin abrasion to get the electrode-to-skin impedance down below 10 kΩ or even 5 kΩ. ADS1299 provides a way to measure Electrode impedance by passing current of known magnitude and frequency on all the 8-channels using a built-in current source. Magnitudes and frequencies that the current source supports are given in figure 20.

Lead-off current magnitude These bits determine the magnitude of current for the current lead-off mode. 00 : 6 nA 01 : 24 nA 10 : 6 μA 11 : 24 μA
Lead-off frequency These bits determine the frequency of lead-off detect for each channel. 00 : DC lead-off detection 01 : AC lead-off detection at 7.8 Hz ($f_{CLK} / 2^{18}$) 10 : AC lead-off detection at 31.2 Hz ($f_{CLK} / 2^{16}$) 11 : AC lead-off detection at f_{DR} / 4

Figure 20: Lead-off Current Magnitude and Frequency [6]

We managed to measure the impedance of the electrodes by passing a current of 6 μA at a frequency of 31.2 Hz. Then after processing which includes filtering out the signal at 31.2 Hz and using Ohm’s Law to calculate the impedance. The voltage drop across the skin-electrode impedance is then measured as we normally measure any EEG signal and then its rms value is calculated. Finally, we got impedance using ohm's law which turns out to be 6.2 kΩ. As we are using 2.2 kΩ resistor boxes on board so subtracting them results in net impedance of 4kOhm which is expected. Figure 21 shows the impedance of the electrode.

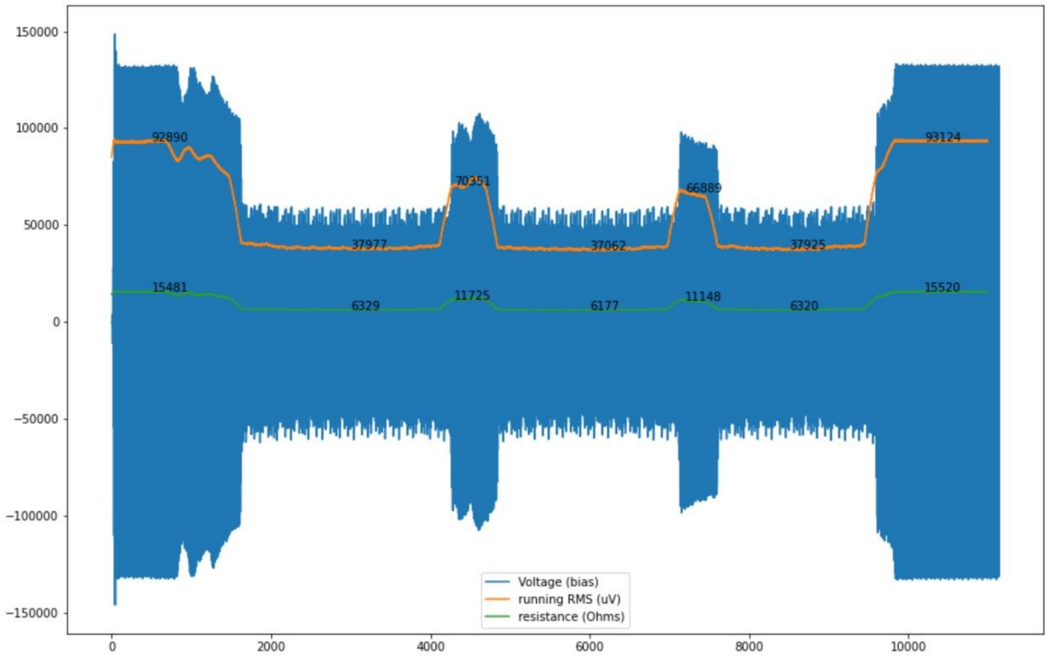

Figure 21: Electrode Impedance using AC Lead-off. It can be clearly seen that the impedance is higher when the electrodes are not firmly connected to the scalp and vice versa.

Chapter Summary

This chapter discusses the methods used to validate the correct working of our EEG device by verifying the 24-bit data received while measuring different signals of known frequencies and amplitudes. It includes graphs from experiments used to record EEG waves including alpha waves as well as EMG artifacts like eye blink and jaw clench. Finally, results for lead-off detection are presented which show the effect of loose electrode connections on the electrode-skin impedance.

Chapter 8

CONCLUSION AND FUTURE WORK

8.1 Conclusion

With this project, we were able to develop an indigenous modular, low-cost EEG data acquisition system titled "sEEGs" which is capable of collecting data from eight channels simultaneously with the capability of being further expanded to sixteen channels. Our device incorporates features like RC noise removing circuitry, lead-off detection for electrode-skin impedance, SD-Card storage of recorded data, accelerometer data of head-movement, live data streaming, real time FFT, and concentration monitoring using our Graphical User Interface(GUI). Our device is also capable of transmitting the signal to other devices via Bluetooth or aerial communication e.g., to a mobile device having any Bluetooth terminal application.

8.2 Future work

We will be collaborating with Military Hospital Pakistan for data collection. After prototyping and verifying the proper functioning of all the features of our device we are moving all the modules including our microcontroller, SD card module, accelerometer and ADS1299 PCB in a single package. It will improve the ergonomics and also ease the data collection process without worrying about the different connections. We have completed the design of the PCB which is shown in.

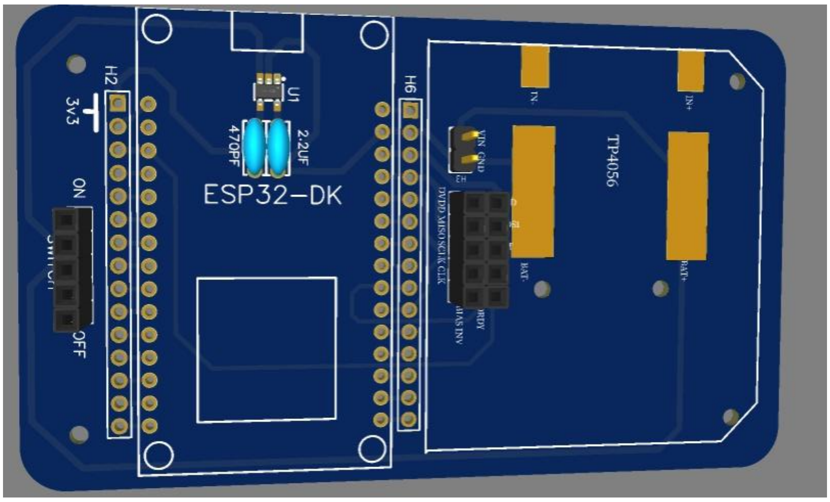

Figure 22: PCB design with all components in a single package

Our project opens doors for a lot of exciting opportunities which utilizes our EEG data collection framework. Due to its low cost, light weight, and low power consumption, it can be used in wearable devices. One such example is electrodes placed on headphones either on the headband or on the ear cup to investigate the mental state of an individual in their routine and is shown in figure 23. This will help us in better understanding of the triggers which invokes emotions of anger, depression, or sadness etc.

Figure 23: Headphones CAD Model and prototype, equipped with hardware [27]

Chapter Summary

This chapter concludes the report by summarizing the major features of our project. It presents recommendations for future work which utilizes this framework.

Chapter 9

REFERENCES

References

[1] World Health Organization, "Epilepsy Fact Sheet," May 2016. [Online]. Available: https://www.who.int/en/news-room/fact-sheets/detail/epilepsy.

[2] F. Siddiqui, T. Sultan, S. Mustafa and S. Siddiqui, "Epilepsy in pakistan: national guidelines for clinicians," *Pakistan Journal of Neurological Sciences,* vol. 10, no. 3, pp. 47-62, 2015.

[3] S. C. Schachter, "EEG," 2017. [Online]. Available: https://www.epilepsy.com/learn/diagnosis/eeg.

[4] S. Debener, "How about taking a low-cost, small, and wireless EEG for a walk?," *Psychophysiology,* vol. 49, pp. 1617-1621, 2012.

[5] T. Uktveris and J. Vacius, "Development of a Modular Board for EEG Signal Acquisition," *Sensors,* vol. 18, no. 7, p. 2140, 2018.

[6] Texas Instruments, *Low-noise, 8-Channel, 24 bits Analog Frontend for Biopotential Measurements,* 2017.

[7] F. Pinho, "Wireless and wearable EEG acquisition platform for ambulatory monitoring," *IEEE 3rd International Conference on Serious Games and Applications for Health,* pp. 1-7, 2014.

[8] S. Feng, "EEGu2: An embedded device for brain/body signal acquisition and processing," *Proceedings of the 27th International Symposium on Rapid System Prototyping: Shortening the Path from Specification to Prototype,* pp. 19-25, 2016.

[9] T. T. Vo, "WEEGEE: Wireless 8-Channel EEG Recording Device," *International Conference on the Development of Biomedical Engineering in Vietnam,* pp. 67-70, 2017.

[10] V. Nathan, "A 16-channel bluetooth enabled wearable EEG platform with dry-contact electrodes for brain computer interface," *Proceedings of the 4th Conference on Wireless Health,* pp. 1-2, 2013.

[11] OpenBCI, [Online]. Available: https://openbci.com/.

[12] J. Frey, *Comparison of an open-hardware electroencephalography amplifier with medical grade device in brain-computer interface applications,* 2016.

[13] T. Radüntz, "Signal quality evaluation of emerging EEG devices," *Frontiers in physiology,* vol. 9, p. 98, 2018.

[14] A. Ramos-Murguialday, "Brain–machine interface in chronic stroke rehabilitation: a controlled study," *Annals of neurology,* vol. 74, no. 1, pp. 100-108, 2013.

[15] H. Cai, "Pervasive EEG diagnosis of depression using deep belief network with three-electrodes EEG collector," *IEEE International Conference on Bioinformatics and Biomedicine (BIBM),* pp. 1239-1246, 2016.

[16] M. Hügle, "Early seizure detection with an energy-efficient convolutional neural network on an implantable microcontroller," *International Joint Conference on Neural Networks (IJCNN),* pp. 1-7, 2018.

[17] M. A. Malik, R. M. Akram, M. A. Tarar and A. Sultan, "Childhood Epilepsy," *Journal of the College of Physicians and Surgeons Pakistan,* vol. 21, no. 2, pp. 74-78.

[18] K. Mustafa, "Just one neurologist for 1m Pakistanis," *The News,* p. 1, 15 May 2011.

[19] M. De Vos, M. Kroesen, R. Emkes and S. Debener, "P300 speller BCI with a mobile EEG system: comparison to a traditional amplifier," *Journal of neural engineering,* vol. 11, no. 3, 2014.

[20] C. Zich, M. De Vos, C. Kranczioch and S. Debener, "Wireless EEG with individualized channel layout enables efficient motor imagery training," *Clinical Neurophysiology,* vol. 126, no. 4, pp. 698-710, 2015.

[21] H. H. Jasper, "The ten-twenty electrode system of the International Federation.," *Electroencephalogr. Clin. Neurophysiol.,* vol. 10, pp. 370-375, 1958.

[22] B. Graimann, B. Allison and G. Pfurtscheller, Brain-Computer Interfaces: Revolutionizing Human-Computer Interaction, Springer, 2010.

[23] A. de Cheveigné, "Filters: when, why, and how (not) to use them," *Neuron,* vol. 102, no. 2, pp. 280-293, 2019.

[24] I. Grout, Digital Systems Design with FPGAs and CPLDs, 2008.

[25] W. Zgallai, Ed., Biomedical Signal Processing and Artificial Intelligence in Healthcare, Elsevier, 2020.

[26] B. J. Baars and N. M. Gage, Cognition, Brain, and Consciousness: Introduction to Cognitive Neuroscience, Elsevier, 2010.

[27] D. D. Mauro, Caruso: Interactive headphones for a dynamic 3D audio application in the cultural heritage context, ResearchGate, 2014.

[28] S. S. Daud, *Butterworth Bandpass and Stationary Wavelet Transform Filter Comparison for Electroencephalography Signal,* 6 ed., International Conference on Intelligent Systems, Modelling and Simulation, 2015.

[29] T. Alotaiby, F. E. Abd El-Samie, S. A. Alshebeili and I. Ahmed, "A review of channel selection algorithms for EEG signal processing," *EURASIP Journal on Advances in Signal Processing,* vol. 2015, no. 1, pp. 1-21, 2015.

Appendices

Appendix A: Glossary

IEEE	Institute of Electrical and Electronics Engineers
WHO	World Health Organization
EEG	Electroencephalogram
BCI	Brain Computer Interface
ADC	Analogue to Digital Converter
TI	Texas Instruments
DAAD	German Academic Exchange Service
AI	Artificial Intelligence
SPS	Samples per Second
SPI	Serial Peripheral Interface
UART	Universal Asynchronous Receiver Transmitter
I2C	Inter-Integrated circuit

Appendix B: Project Poster

Development of a Modular EEG Framework for Teaching, Training and Data Collection

Advisor: Dr. Faisal Shafait **Co-Advisor**: Mr. Imran Abeel
Amna Ahmed Gillani, Syed Shayan Sohail, Syed Momin Ali Hashmi

Problem Statement

Traditional EEG technology consists of bulky hardware and fragile wired sensors for data acquisition. Expert knowledge is needed to interpret EEG signals. People living in the rural areas of Pakistan do not have access to expensive devices and trained neurologists.

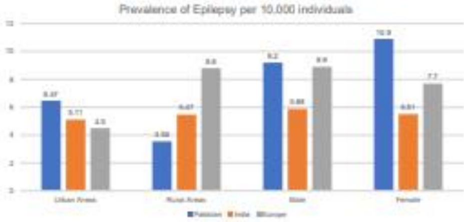

Fig: Prevalence of epilepsy in Pakistan, India and Europe

Objectives

Develop a low-cost, wearable device

- Low-cost tool for the recording of EEG data in rural and urban areas where specialized facilities are not available

Analyze EEG data

- Data can be recorded and shared to a smartphone via Bluetooth
- Custom GUI will be used to process and display 8 channel data.

Tools & Acknowledgements

DAAD

Materials & Methodology

Using microcontroller to interface with our ADS1299 based custom PCB we can obtain raw EEG signals.

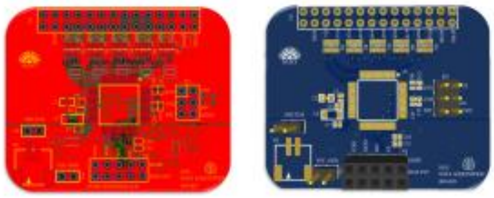

Fig: Custom data acquisition board

Proposed Solution

The proposed solution is to develop a modular hardware device which utilizes the ADS1299 ADC to record 8 channels of EEG data. The devices can be stacked to increase the number of channels in multiples of 8. The data is sent to a smartphone application via Bluetooth. Alpha waves will be used to monitor concentration levels and for simple 1-D control.

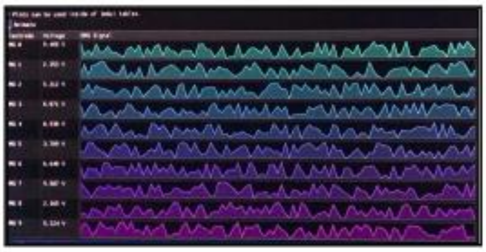

Fig: 8-Channel EMG data from custom board