REPUBLIC OF TURKEY
ADANA ALPARSLAN TÜRKEŞ SCIENCE AND TECHNOLOGY UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

DESIGN AND DEVELOPMENT OF A WIRELESS EEG DEVICE AND OPEN SOURCE SOFTWARE

HİMMET AYYILDIZ
MASTER OF SCIENCE

ADANA 2022

REPUBLIC OF TURKEY

ADANA ALPARSLAN TÜRKEŞ SCIENCE AND TECHNOLOGY UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

DESIGN AND DEVELOPMENT OF A WIRELESS EEG DEVICE AND OPEN SOURCE SOFTWARE

HİMMET AYYILDIZ

MASTER OF SCIENCE

SUPERVISOR

Assoc. Prof. Dr. Esen YILDIRIM

ADANA 2022

I hereby declare that all information in this thesis has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all information that is not original to this work.

[Signature]

Himmet AYYILDIZ

ABSTRACT

DESIGN AND DEVELOPMENT OF A WIRELESS EEG DEVICE AND OPEN SOURCE SOFTWARE

Himmet AYYILDIZ

Department of Electrical-Electronic Engineering

Supervisor: Assoc. Prof. Dr. Esen YILDIRIM

February 2022, 60 pages

In the last century, EEG has been a diagnostic method used in the detection of many diseases. Today, with the rapid development of computer technologies, EEG technology has begun to be used not only for disease diagnosis but also as a method to establish a connection between the brain and the computer. Humanity has long dreamed of connecting with computers and controlling them efficiently just by thinking without any physical interaction. It seems clear that one of the most suitable methods for this purpose is non-invasive EEG measurements, as it is easy to apply and does not require a medical procedure. This study aims to design a cost-effective and open-source device, to create a prototype, and to test the accuracy and consistency of the resulting device for researchers who want to measure EEG signals and make various researches on them or develop devices that will serve various special purposes. The design and production of the device can be grouped under three main groups; electronics, mechanics, and software parts. In the electronics part; ADS1299, an 8-channel integrated chip that offers low-noise 24-bit analog-to-digital conversion resolution, produced by Texas instrument company, which is currently used in many EEG devices, ESP32-WROOM microcontroller, which controls this integrated chip, reads, processes and transfers the data to the computer via Bluetooth communication, provides power to the system. 2 18650 Li-po 3.7 volt batteries and battery control system and dry type electrode produced by OpenBCI Company were used as the electrode. In the mechanical part, a cap was designed inspired by the Ultracortex Mark III and Ultracortex Mark IV cap of OpenBCI Company, and boxes providing enclosures for the produced circuits were designed and all of them were manufactured using a 3D printer. In the software part; there is embedded software written in C language on the chip that runs on the device, receives the data, processes it, and sends it to the computer. In addition, a Visual user

interface that works on the computer side, receives and processes the data sent by the device, displays them in graphics, and saves them to a file, has been designed and coded in C# using Visual Studio. After the prototype of the device was revealed, the signals received from the device were examined and their consistency was evaluated.

Keywords: eeg, visual stimulation, esp32, ads1299, dry electrode

ÖZET

KABLOSUZ EEG CİHAZI VE AÇIK KAYNAK YAZILIMLARININ TASARIMI VE GELİŞTİRİLMESİ

Himmet AYYILDIZ

Elektrik Elektronik Mühendisliği Anabilim Dalı

Danışman: Doç. Dr. Esen YILDIRIM

Şubat 2022, 60 sayfa

Son yüzyılda, EEG birçok hastalığın tespitinde kullanılan bir teşhis yöntemi olmuştur. Günümüze geldiğimizde, bilgisayar teknolojilerin çok hızlı bir biçimde gelişmesiyle. EEG teknolojisi sadece hastalık teşhisi için değil, aynı zamanda beyin ve bilgisayar arasında bağlantı kurmak için bir yöntem olarak kullanılmaya başlanmıştır. İnsanlık, uzun süredir herhangi bir fiziksel etkileşim kurmadan sadece düşünerek bilgisayarlarla bağlantı kurmayı ve verimli bir şekilde onları kontrol etmeyi hayal etmektedir. Açıkça görünmektedir ki gerek kolay uygulanabilirliği gerekse tıbbı bir işlem gerektirmemesiyle bu amaca en uygun yöntemlerden birisi de invaziv olmayan EEG ölçümleridir. Bu çalışmanın amacı, EEG sinyallerini ölçerek bunlar üzerinde çeşitli araştırmalar yapacak veya çeşitli özel amaçlara hizmet edecek cihazlar geliştirmek isteyen araştırmacılara, uygun maliyetli ve açık kaynak bir cihazın tasarımını yapmak, prototipini oluşturmak ve ortaya çıkan cihazın testlerini yaparak doğruluk ve tutarlığını tespit etmektir. Cihazın tasarımı ve üretilmesi üç ana başlıkta toplanabilir. Elektronik kısmında; şuan da birçok EEG cihazında kullanılan Teksas Instrument şirketinin ürettiği ADS1299 düşük gürültülü 24 bit analogdan dijitale çevirim çözünürlüğü sunan 8 kanallı bir tümleşik çip, bu tümleşik çipi kontrol eden, verileri okuyan, işleyen ve Bluetooth haberleşmeyle bilgisayara aktaran ESP32-WROOM mikro denetleyicisi, sisteme güç sağlamak için 2 adet 18650 Li-po 3,7 volt pil ve batarya kontrol sistemi ve Elektrot olarak da OpenBCI şirketinin ürettiği kuru tip elektrot kullanılmıştır. Mekanik kısımda OpenBCI şirketinin Ultracortex Mark III ve Ultracortex Mark IV isimli kepinden esinlenerek bir kep tasarımı yapılmış ayrıca üretilen devreler için muhafaza sağlayan kutular tasarlanıp, bunların hepsi 3B yazıcı kullanılarak imal edilmiştir. Yazılım kısmında; Cihazın üzerinde çalışan, verileri alıp, işleyip bilgisayara gönderen çipin üzerinde gömülü C dilinde yazılmış gömülü yazılım bulunmaktadır. Ayrıca bilgisayar tarafında çalışan, cihazın gönderdiği verileri alıp işleyen, bunları grafiklerde gösteren ve dosyaya kaydeden bir Görsel kullanıcı ara yüzü tasarlanıp Visual Studio kullnılarak C# dilinde kodlanmıştır. Cihazın prototipi ortaya çıktıktan sonra, cihazdan alınan sinyaller incelenmiş ve tutarlılığı değerlendirilmiştir.

Anahtar Kelimeler: eeg, görsel uyarım, esp32, ads1299, kuru elektrot

Dedication

I would like to dedicate my thesis to my family.

ACKNOWLEDGEMENTS

I sincerely appreciate my thesis supervisor, Associate Professor Doctor Esen YILDIRIM, who directed me to work on my thesis and gave support and encouragement when I encountered challenges, for her important advice and encouragement.

I would like to express my gratitude to M. Sait KARASOY, İhsan TÜRKCAN, Sebahattin KARGA and Elanur EKİCİ, as well as my brother Yunus Emre AYYILDIZ, who gave me with financial and moral support when I was preparing this thesis.

Finally, I'd want to express my heartfelt thanks to my loving parents, who raised me and led me to where I am now, and who did not spare me all of their patience and support, without demanding anything in return.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVATIONS / NOMENCLATURE

fMRI	: Functional magnetic resonance imaging
EEG	: Electroencephalography
BCI	: Brain Computer Interface
EMG	: Electromyography
EOG	: Electrooculography
A/D	: Analog to Digital
EP	: Evoked Potentials
ERP	: Event-Related Potentials
C+	: Cations
A-	: Anions
AgCl	: Silver chloride
HCl	: Hydrochloric acid
NaCl	: Salt
ADC	: Analog-to-digital converter
DAC	: Digital to Analog Converter
ALS	: Amyotrophic Lateral Sclerosis
MS	: Multiple Sclerosis
FDA	: Food and Drug Administration
WIFI	: Wireless Fidelity
UART	: universal asynchronous receiver-transmitter
GPIO	: General Purpose Input/output
SDIO	: Secure Digital Input Output
SD card	: Secure Digital cards
PWM	: Pulse Width Modulation
I2C	: Inter-Integrated Circuit
GND	: Ground
RTC	: Real time clock
SPI	: Serial Peripheral Interface
CLK	: Clock
MOSI	: Master Output → Slave Input

MISO	: Master Input→ Slave Output
SDA	: Serial Data Line
DC	: Direct Current
CAN	: Controller area network
BLE	: Bluetooth low energy
AFH	: Adaptive Frequency Hopping
SAR	: Specific absorption rate
LED	: light-emitting diode
PGA	: Programmable gain amplifier
BIS	: Bispectral Index
ΔΣ	: Delta-sigma
FFT	: Fast Fourier Transform
3D	: 3 Dimension
USB	: Universal Serial Bus
STL	: Standard Triangle Language
PLA	: Polylactic acid
IDE	: integrated development environment
PCB	: Printed Circuit Board
Hz	: Hertz
MHz	: Mega hertz
Mm	: Millimeter
µA	: Micro Ampere
V	: Volt

1. INTRODUCTION

The human brain and its working principle is a subject that scientists are constantly wondering and working on. The primary methods that shed light on brain functioning brain are fMRI (Functional magnetic resonance imaging) and EEG (Electroencephalography). EEG devices are widely used because they are less costly and easier to use than other methods (Memon & Waheed, 2018). EEG is a method that enables the measurement of the potential difference resulting from the synaptic stimulation of neurons and electrochemical activity in the brain. It can be classified into five signal groups according to their frequency ranges. These frequency groups are:

- Delta: Has a frequency of 3 Hz or less. They tend to be the loudest and slowest waves in terms of amplitude. It is normal as the dominant rhythm in infants up to one-year-old and in stages 3 and 4 of sleep. It is usually most prominent from the front in adults(Sahin et al., 2015).
- Theta: Has a frequency of 3.5 to 7.5 Hz and is classified as "slow" activity. It is normal in children up to 13 years of age and completely normal in sleep and abnormal in awake adults(Sahin et al., 2015).
- Alpha: It has a frequency between 7.5 and 13 Hz. It is usually seen in the posterior regions of the head on both sides and the amplitude is higher on the dominant side. It occurs when closing and relaxing the eyes and disappears when opening the eyes or stimulating by any mechanism (thinking, calculation). It is the main rhythm seen in normal relaxed adults. It is found in almost all ages, especially after the thirteenth year (Nacy & Kbah, 2016).
- Beta activity is defined as "rapid" activity. It has a frequency of at least 14 Hz. It is more noticeable from the front and is generally found on both sides in a symmetrical distribution. It's usually seen to be a healthy beat. It is the most common rhythm among patients who are alert, worried, or open-eyed.
- Gamma: waves are those that have a frequency between 30 and 100 Hz. These waves are related with various motor processes in a healthy person, such as muscular activity. EEG-based BCI systems rarely use gamma waves because they are easily influenced by artifacts like electromyography (EMG) or electrooculography (EOG).

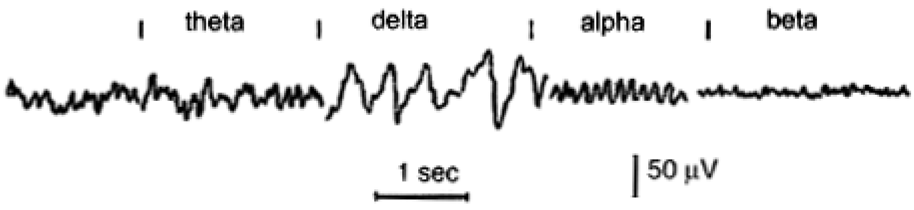

Figure 1.1 EEG frequency representation (Memon & Waheed, 2018)

The scalp surface can be used to measure EEG signals, and it may not be necessary to drill a hole in the skull as in the invasive case and reach the brain to capture the signals. This feature of the EEG method makes it the most well-known technique among researchers doing research in the field of BCI. However, there are some difficulties to be overcome in order to use the EEG signals acquired by the noninvasive method to construct BCI systems. The problem is that the quality of the EEG signal recorded from the scalp is very poor because the potential difference created on the side of the brain suffers the effects of attenuation, scattering and turbidity as it passes through the skull, scalp and many other layers (Balim & Acir, 2018). This means that it is not so easy to obtain reliable EEG signals from the scalp. Also, the EEG signal (with amplitude of the order of 1-100µV) is very prone to be affected by various noise sources in the environment (Eraldemir et al., 2020). External sources, mains and internal sources that can produce 50 Hz background noise cause flickering, thermal, popping and acquisition noises. As a result, the EEG signal acquisition stage must include a high-quality EEG signal acquisition equipment (electrodes, amplifiers, and A/D converters) that not only captures the signal but also protects it from noise (Sahin et al., 2015).

The EEG signal is generated by determining the potential difference between a certain electrode location (active position) and the reference electrode position. The differential voltage signal between the active and reference positions is also received at a third electrode location (known as the ground position), which is directly linked to the common point of the electronic circuit. To get the EEG signal from a point above the head, a minimum of three electrodes are necessary. To acquire repeatable findings from many recordings, the actual positions of the electrodes on the scalp were initially determined by adopting the 10-20 international system (*International 10-20 System*, 2021). The worldwide 10-20 method standardizes EEG electrode placement by using external landmarks and standard electrode spacing. The angles between the electrode arrays are what give the numerals 10-20 their meaning. To define electrode placements, it employs two spots on the skull as a guide. "Nasion" and "Inion" are the names of two of these two reference points. Inion is found in the bony hump at the base of the skull, while Nasion is visible above the nose at eye level. Figure 1.2 is a schematic of the 10-20 international system.

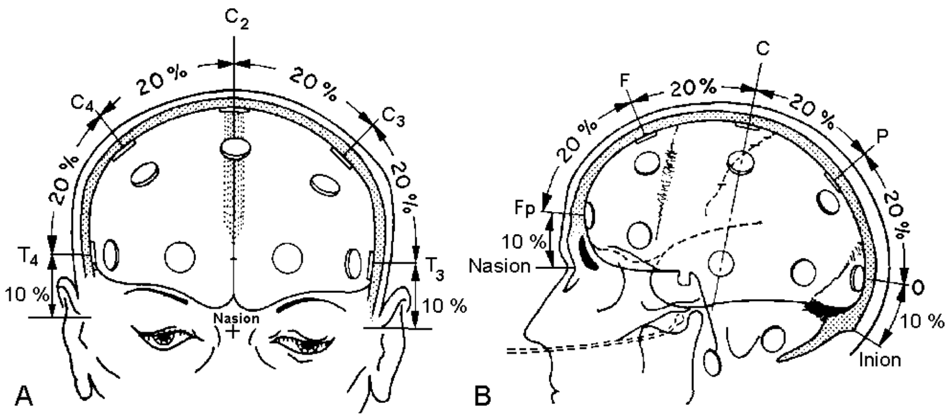

Figure 1.2 International 10-20 system (*International 10-20 System*, 2021)

EEG devices are used both in the diagnosis of many diseases medically and in many other disciplines for non-clinical purposes to understand the underlying features of the working brain. A very common example is Brain-Computer Interface (or Human-Machine Interface). Another area of use is to develop systems that will create meaningful patterns and make inferences about EEG signals with machine learning methods. For non-clinical use, EEG devices are mostly used by professional groups who do not have medical knowledge; such as programmers, engineers or technical persons. For this reason, ease of use and being ready to use without requiring much preparation is a highly desired feature for EEG devices. There are some EEG devices available on the market for non-clinical use. However, these devices have some disadvantages for researchers; high cost, difficulty to use, noise interference with signals, too cumbersome to transport, insufficient samples per second, and most importantly, companies forcing researchers to use expensive non-open source software.

1.1. The objective of the thesis

The main purpose of this thesis is to develop a portable EEG device that can be easily attached to the scalp without the use of solutions, gels, pastes, and an open-source computer interface that provides wireless communication and actively prevents unwanted distortions called artifacts in EEG. In addition, experimental studies will be carried out for the validation of the device to be developed and, if necessary, error corrections and optimization studies will be carried out until the desired results are obtained according to the results obtained from these studies.

1.2. The outline of the thesis

In this part of the thesis, the main lines of the study are explained in general. First of all, literature studies were conducted on the formation of EEG signals, the structure of the brain and EEG devices, as required by the subject of the study. An EEG device with the desired features was designed with the data obtained from the literature studies and improvements were made by keeping the cost and quality in the foreground. In the material and method section, information is given about the materials used in the device and the construction processes of the device. In the conclusion part, it has been examined whether the produced device meets the desired features. It is emphasized whether the resulting device meets the requirements, and if not, what solutions can be produced, and how this study can be made more useful and scientifically beneficial in the future.

2. LITERATURE REVIEW

2.1. Brain

It is an organ that functions in the center of the nervous system. It is located in a protected area surrounded by bones in the skull. The brain basically provides all the coordination of the body, but it is also responsible for other functions such as processing data from the sense organs, thinking, speaking, writing, memory.

The largest part of the brain is the cerebral cortex. It is 2-3 mm thick in the outer part of the brain. It is estimated that it consists of approximately 15-33 billion neurons. Each of the neurons is connected with thousands of neurons by connections called synapses. Neurons also connect with other parts of the brain or related regions in the body with the help of long protoplasmic fibers called axons (Eraldemir et al., 2019). The cerebral cortex (brain shell) consists of 2 regions called hemispheres. Each hemisphere can be divided into 4 lobes called frontal (F), parietal (P), temporal (T), and occipital (O). Frontal lobe is activated for functions such as decision making, controlling emotions, problem-solving; parietal lobe for visual and tactile perception, recognition and orientation; temporal lobe for hearing, long-term memory, speech, and occipital lobe for predominantly visual perception. Parts of the brain are shown in Figure 2.1.

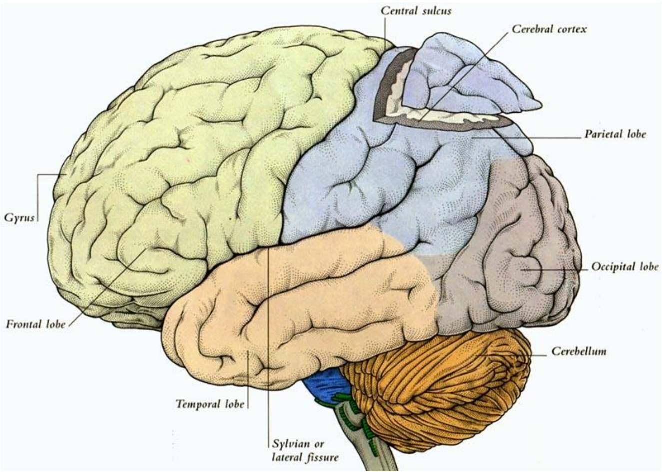

Figure 2.1 Parts of the brain (Penney, 2022)

The entire brain and all these regions are actually made up of a single cell type, nerve cells, namely neurons (Nacy & Kbah, 2016).

2.1.1. Neuron

The nerve cell, often known as a neuron, is the nervous system's basic functioning unit. Its primary role is to transfer information. The human nervous system is thought to have around 100 billion neurons. A typical nerve cell is linked to between 50,000 and 250,000 different neurons. Depending on the sort of specialized function they perform, they might appear in a range of forms and sizes. Soma, dendrites, axon, and terminal buttons are the four structures that make up the vast majority of neurons. Figure 2.2 represents the parts of a neuron.

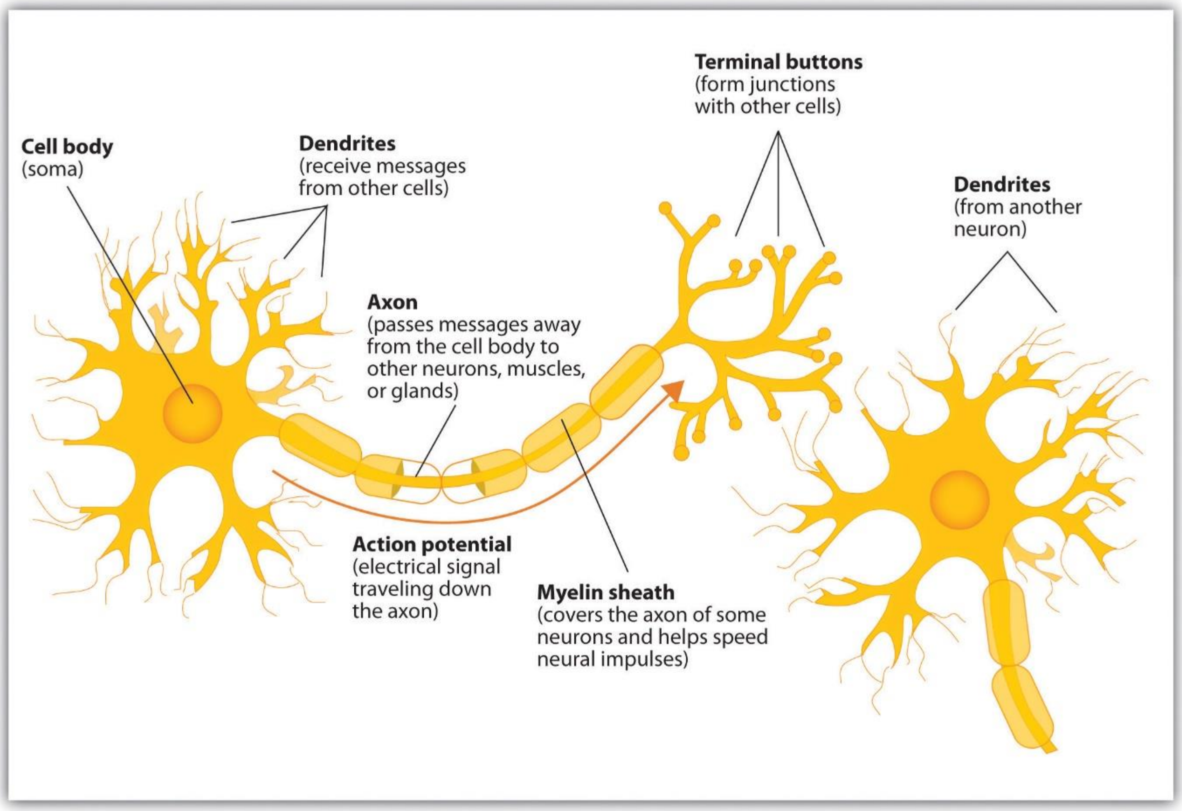

Figure 2.2 Components of the Neuron (Stangor & Walinga, 2014)

Dendrites are important receptors for neural communication. Messages passing from one neuron to another are transmitted/transmitted through synapses, which are the junctions between the terminal buttons of the cell sending the message and the dendritic membrane or soma (cell body) part of the cell receiving the message. Synapses are specialized junctions that allow neurons (nerve cells) to transmit messages to other neurons or non-neuronal cells such as muscles or glands. The chemical synapse between a motor neuron and a muscle cell is also called the neuromuscular junction. The axon, another part of the neuron, is a long, thin tube often covered with a myelin sheath. The main function of the axon is to carry information from the cell body to the terminal buttons. This basic message carried by the axon is called the action potential. An action potential is an electrical/chemical event similar to a short pulse. The action potential in all axons is always of the same magnitude and speed. Although the action potential divides when it reaches the branches of the axon, it does not lose its measure. In other words, each axon branch receives an action potential at full strength. Terminal buttons are small nodules at the ends of thin branches of axons. Terminal buttons release chemicals called neurotransmitters when an action potential reaches them. Neurotransmitters excite or inhibit (inhibit) the receiving cell. In this way, it determines whether an action potential will occur in the axon of the other cell (Stangor & Walinga, 2014).

2.1.2. Action Potential

An action potential is a quick rise and fall of a cell's electrical membrane potential in electrophysiology. Neuron action potentials are also known as "nerve impulses" or "spikes," and a neuron's "spike train" is the temporal sequence of action potentials it produces (Sahin et al., 2015). The change of the potential difference in the neuron with respect to time is shown in the graph in the Figure 2.3.

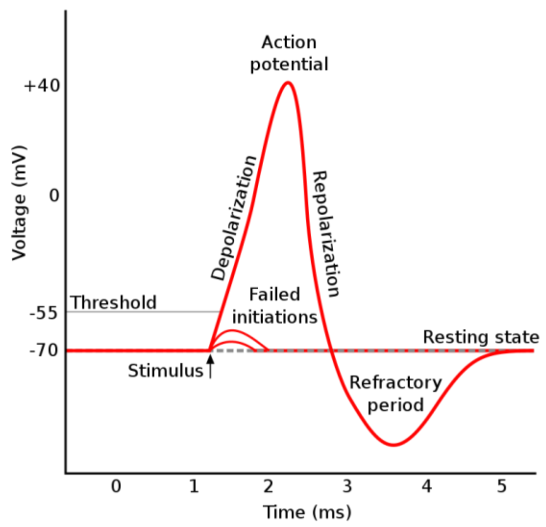

Figure 2.3 Action potential (“Action Potential,” 2021)

2.2. EEG

EEG is an electrophysiological monitoring method of the macroscopic effects of electrode potentials generated during brain activities, through electrodes placed on the skull.

An ionic current inside the neurons of the brain causes voltage variations, which are measured by EEG. EEG stands for electroencephalography, which is the recording of the brain's spontaneous electrical activity over time using several electrodes on the scalp.

Today, EEG signals are frequently used for understanding and investigating the neurological functions and neuropsychological properties of the brain, as well as for many clinical purposes for diagnosis and treatment. The purposes of using EEG signals in fields of application such as medicine, clinical psychology, cognitive sciences, and biomedical engineering and in a wider range of academic research can be summarized as follows:

- Detection of alertness, coma and brain death,
- Damages that may occur due to brain hemorrhage, trauma or tumors
- Determination of regions
- Testing evoked potentials and neural pathways
- Biofeedback,
- Control of anesthesia stage in surgeries,
- Alpha rhythm tracking,
- Diagnosis of epilepsy and determination of the onset of seizures,
- Determining the side effects of epilepsy drugs,
- Monitoring the development of the brain,
- Researching sleep disorders and sleep psychology,
- Identification of mental diseases,
- Provide information alongside brain imaging techniques.

2.2.1. Generation of EEG Signals

Neurons differ from other body cells in their ability to rapidly transmit signals over long distances. Neurons carry out the task of carrying signals by generating action potentials, which are characteristic electrical pulses that can act chemically on neural networks. Signals coming to neurons are processed into information by firing action potential chains, and the resulting information is transmitted to other neurons by firing action potential chains. Most of the cells in the human brain have the ability to affect others. The largest part of a neuron, the dendrite, processes impulses from other cells and transmits them to the axon by passing it along its myelin-covered extension. The information processed by the chemical activity in the axon is transferred to other cells.

Action potentials are realized by the chemical movement of ions in the cell membrane. There are three states for chemical action: In the active state, the passage of ions (sodium and potassium) is possible in the cell.

When a cell in a resting state is activated by any stimuli, the resting potential of the cell membrane changes within milliseconds and achieves a positive value. Depolarization is a condition in which the inside of the membrane obtains a higher positive value than the outside. Without remaining in this state, the membrane potential recovers to its original resting potential in a relatively short period. Repolarization is defined as the return of membrane potential from depolarization to resting potential. Depolarization and repolarization make up an action potential.

2.2.2. Obtaining EEG Signals

EEG signals are obtained from the inside or surface of the brain in limited and special cases, mostly through electrodes placed on the skull. Measurements, which were previously performed by scraping the hair of the subjects and sticking the electrodes to the skull, are now made using electrode caps with the development of technology. A fluid gel is applied to the electrode inlets, which are placed at certain distances on the cap, to facilitate the detection of electric current.

The placement of the electrodes in the cap is done according to the international standards determined by the American Electroencephalogram Society. These standards include a large number of technical requirements about the technical characteristics of the electrodes, the angles of placement in the cap, and the system used. The minimum measurement levels determined are important in terms of the international validity and comparability of the experiments. While there are different types of electrode caps available, the most common are those formed to a standard called the 10-20 placement system. The 10-20 system consists of 19 skull and 2 ear electrodes. 20 skull and 1 nose electrodes are sufficient for modern caps used today. The electrodes are placed at angles determined by the cap system and in such a way that they can detect signals over different lobes and are named according to the region they are in.

Ear or nose electrodes are used to calculate the s/r ratio. Each electrode in the cap functions as a channel and the EEG signals are recorded as unipolar or bipolar as preferred. Whether the recording is unipolar or bipolar is related to the connection of the electrodes and is preferred according to how the polarization problem will be handled in the research. In unipolar recordings, one electrode also receives signals from nearby areas, while bipolar recordings give more sensitive results because they observe the potential difference in close areas. In advanced experiments, caps consisting of 32, 64 or even 128 electrodes can be used. 10-20 shows the docking system, and the Figure 2.4 shows the same system from different angles.

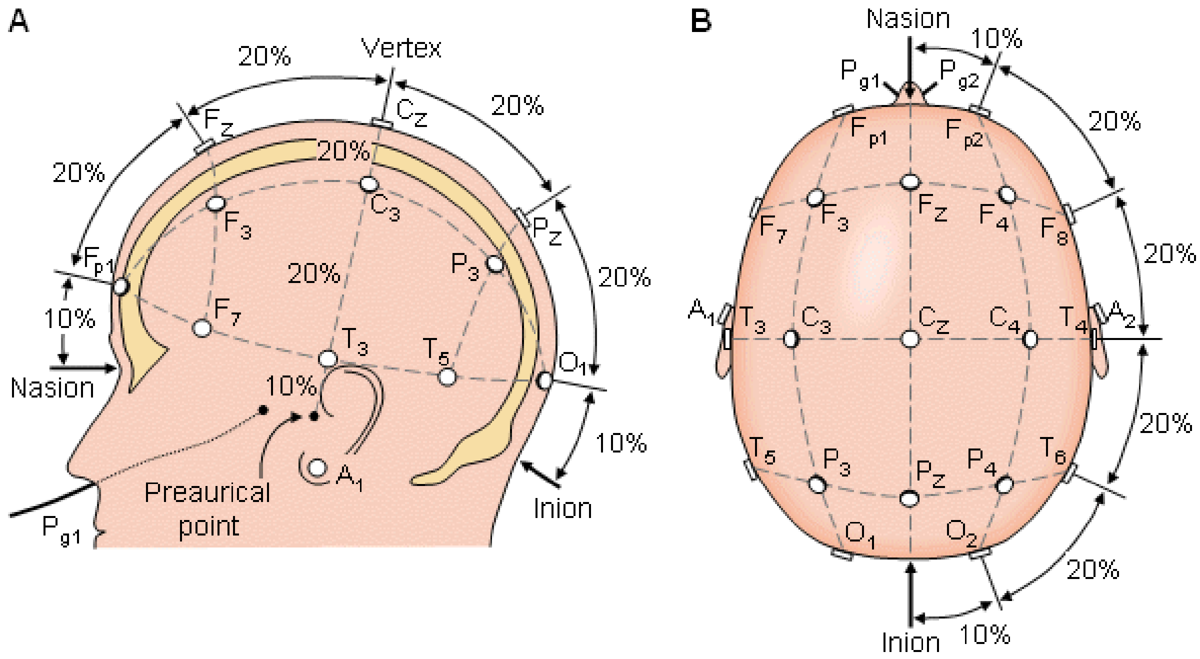

Figure 2.4 International 10-20 system from top and side view (Sahin et al., 2015)

2.2.3. Evoked Potentials (EP)

The spontaneous electrical activity of the brain can be affected by any external stimulus (sound, light, etc.). The electrical activity that changes as a result of these stimuli is called evoked potentials (EP). Evoked potentials are usually responses to a uniform stimulus (for example, a steady tone) (Sahin et al., 2015).

2.2.4. Event-Related Potentials (ERP)

EEG activity includes the activities produced naturally by the brain, as well as its responses to an external stimulus. Event-related potentials (ERPs) are potentials that appear in the EEG after a specific stimulus (target stimulus) (Sahin et al., 2015).

2.3. Electrodes

Transducers that convert ionic potentials and currents into electric potentials or currents are needed to measure bioelectric potentials. A transducer for detecting electrical biological signals is made up of two electrodes that measure the ionic potential difference between the points where the electrodes are attached. Except for a few unique applications, measuring the individual action potentials produced by each cell is extremely difficult, if not impossible. Because electrodes must be placed into the cell sensitively (*Biyomedikal Cihaz Teknolojileri,Elektrotlar*, 2011).

2.3.1. Biopotential Electrode

Electrodes are the components that provide as a link between the device and the location where electrical current in the human body is measured, recorded, and transmitted to electronic equipment. While ions carry current in the body, electrons carry current in the electrode, resulting in a charge transfer between the two. This operating system is shown in Figure 2.5.

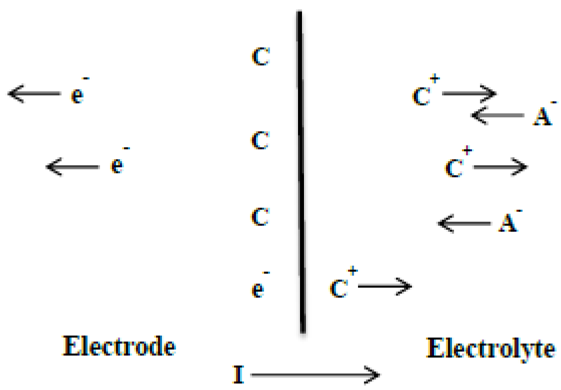

Figure 2.5 Charge transfer between electrode and Electrolyte (Özdamar, 2009)

The process of converting the ion current of the electrodes to the electron current occurs in the liquid medium (electrolyte) in which the electrodes are located and at the interface close to the electrode. Electrons are present on the electrode side of this interface, and cations (C+) and anions (A-) are on the electrolyte side. Considering the situation in which there are cations from the electrolyte material used in the electrolyte, the electrode atoms lose their electrodes and become cations (positive ions) in the electrolyte or, on the contrary, the cations from the electrode material in the electrolyte accumulate on the electrode surface by stealing electrons from the electrode (Özdamar, 2009).

2.3.2. Dry Electrodes

Ag/AgCl reversible electrode is widely used for bioelectrical observations. To make an electrode in this way, highly pure metallic silver in the form of a wire or disk is placed in a dilute solution (HCl or NaCl) containing Cl ions, and a direct current of 1 mA/cm2 is passed for a few minutes. The silver surface is coated with a thin AgCl. For example, while such an electrode works as a cathode, Ag+ ions in the AgCl layer are deposited on the silver metal; Cl ions pass into the solution (tissue). While acting as an anode, metallic Ag atoms lose electrons and enter the AgCl layer as Ag+ ions, encountering Cl - ions coming from the tissue, and new AgCl is produced. Thus, the electrode behaves reversibly with the Cl ions (Hendarwin et al., 2019).

2.4. Measuring EEG signals

EEG is acquired by placing electrodes on the scalp and monitoring the electrical potential change of the scalp. The potential difference between the electrodes can then be raised to a usable level before being digitized and stored in a computer for analysis. Because the EEG is a tiny signal with an amplitude in the order of microvolts owing to the summation and blurring effects of volume conduction, acquiring acceptable quality EEG data requires tight constraints on the electrical impedance and noise resistance of the body electrode contact. The transmission line that connects the electrode to the amplifier. Mechanical etching to remove the stratum corneum, the high-impedance top layer of the epidermis composed of dead skin cells, is commonly used to reduce the scalp-electrode impedance, followed by the application of an ionic gel between the electrode and the skin (Balim & Acir, 2018). Hairy parts, like as the head, provide a problem for this impedance reduction procedure and frequently require the use of more gel than would otherwise be required; when maximum signal quality is desired, the hair is usually shaved.

Research continues on dry, through-hair electrodes that match the interface impedance (and thus signal quality) of the conventional type, and although some have even introduced it, wet electrodes remain the gold standard for clinical EEGs

The amplifier itself should also contribute as little noise as possible. Amplifiers and analog-to-digital converters (ADCs) in the past required high voltage sources (eg ±12V or ±5V). Modern amplifiers capable of very high gain are capable of rail-to-rail operation from a single-ended voltage source as low as 5V, 3.3V, or 1.8V. This effect is compounded by the emergence of ultra-low-noise amplifiers and modern analog-to-digital (A/D) techniques that allow data acquisition up to a 24-bit nominal value. As a result, much lower gains can be used (Balim & Acir, 2018). For example, Sigma-delta ADCs greatly oversamples the resulting signal and then use noise shaping filters and decimation to produce a lower rate signal with high precision; Their inherent low-pass filtering means that analog anti-aliasing requirements are much less stringent than with traditional ADCs. These advancements, together with advancements in wireless communication technology, imply that EEG amplifiers, which were originally huge and high-power equipment, may now be downsized to the point of being wearable gadgets.

2.5. EEG devices

A small, wireless, portable EEG system has numerous benefits and uses in both medical and non-medical fields. A mobile EEG device with a wireless connection to a host computer or the Internet, or having enough local storage to record large amounts of data in a home environment would be extremely beneficial for clinicians to be able to learn about patient EEG activity in a natural setting and improve patient outcomes. For example, sleep activity can be monitored at home or a pre-ictal EEG can be analyzed for a patient who has had a seizure during their daily routine rather than in the hospital. A wearable, mobile EEG system could provide a more practical, non-invasive brain-computer interface for patients with disabilities such as ALS or MS patients than traditional bulky designs. On the other hand, a wearable EEG system could enable a wide variety of entertainment applications, from simple focusing games to neurofeedback for relaxation or simply as a new control method for external devices. Some commercial devices are already available to meet this demand. These devices and their specifications are given in the Table 2.1. The device that is developed within the scope of the thesis is named AYYILDIZ-BCI and its specifications are also given in the table.

Table 2.1 EEG device and prototype comparison Table(*EEG-Headset Comparison Table*, n.d.)

	Neuroelectrics Enobio 32	**Emotiv Epoc**	**OpenBCI Cyton**	**ABM B-Alert X24**	**Ayyıldız BCI**
Number of channels	32	14	8	24	8
Sampling rate	500Hz	128Hz	250Hz	256Hz	128-500
Communication	Bluetooth / Wi-Fi	Proprietary wireless	Bluetooth / RFDuino radio	Bluetooth	Bluetooth / Wi-Fi
Operating time	14 hours	12 hours	24 hours	6 hours Bluetooth / 16 hours SD card	24 hours
Weight	65g	125g	260g	110g	270g
Onboard storage	Yes	No	Yes	Yes	No
Accelerometer	Yes	Yes	Yes	Yes	No
Medically certified	CE / FDA investigational	No	No	No	No
Price	$$	$699.00	$ 749.99	>$ 1000	$143

Table 2.2 EEG device and prototype comparison Table(*EEG-Headset Comparison Table*, n.d.)

	AntNeuro eego	**BioSemi**	**g.tec nautilus**	**Cognionics Mobile 72**	**mBrainTrain Smarting**
Number of channels	64	256	64	72	24
Sampling rate	2048Hz	2-16kHz	500Hz	500-1000Hz	250-500Hz
Wireless	Yes (Bluetooth / Wi-Fi)	No	Yes (Bluetooth)	Yes (Bluetooth)	Yes (Bluetooth)
Operating time	6 hours	5 hours (or unlimited when wired)	10 hours	6 hours Bluetooth / 10 hours SD card	5 hours
Weight	500g	1.1kg	360g	250g	60g
Onboard storage	Yes	No	Yes	Yes	No
Accelerometer	Yes	Yes	Yes	Yes	Yes
Medically certified	CE	No	No	No	No
Price	>$ 1000	>$ 10000	>$ 1000	>$ 2000	>$ 2000

3. MATERIALS AND METHODS

The design and production of the prototype is a multidisciplinary subject that concerns many areas and requires engineering skills in many different fields. Because the prototype includes mechanical a design, electronic design and software design parts. However, since the developed device will be used in the human body, it imposes biomedical responsibilities. The prototype should not adversely affect human health for any reason. For this reason, it also includes the field of biomedical engineering. After the prototype is produced, it is necessary to test the accuracy and consistency of the produced device.

In this section, the materials and methods used while designing and producing the prototype, and the preparation and application of the statement prepared to test the device are discussed.

3.1. Materials

Various mechanical and electrical parts are needed to physically produce the prototype. Some of these parts were imported from abroad because they could not be found in the domestic market. Since industrial production is not possible, most of the mechanical parts are manufactured using the additive manufacturing technique using 3D writing. Electronic components are generally used as modules or development boards.

3.1.1. Electronic Materials

Recently, researchers and engineers often use development boards when developing the first prototypes. The reason for this is that prototyping with development cards is fast, the cost is low, and it is open to development. Therefore, for the development of the first prototype of this study, development cards were used in the Electronics section. This saves time and money. Then, based on the developed system, original printed circuit design was made. The development boards used and the designed printed circuit board are explained in detail.

3.1.1.1. ESP32-WROOM-32

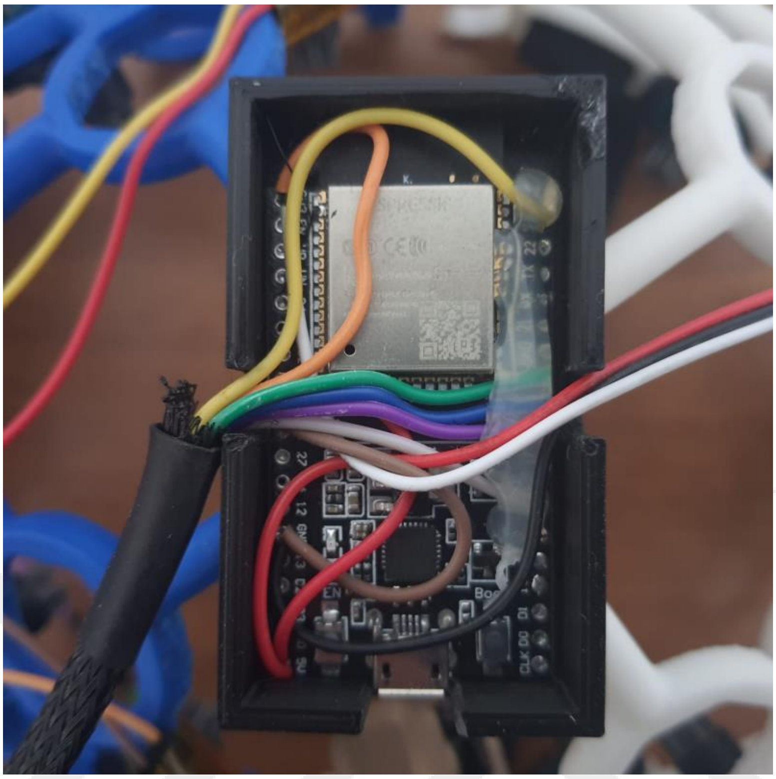

Figure 3.1 ESP32 WROOM used in project

Features:

802.11b/g/n (802.11n, up to 150Mbps) The frequency range for WIFI is 2.4GHz to 2.5GHz. Support for RTOS, clock frequency modification range of 80 MHz to 240 MHz Built-in 12-bit high-precision ADC with up to 18 channels, with two channels. UART/GPIO/ADC/DAC/SDIO/SD card/PWM/I2C/I2S interfaces are supported. Multiple sleep modes are supported. The sleep current of the ESP32 chip is less than 5μA. Lwip protocol stack embedded, STA/AP/STA + AP operating modes are supported. Remote firmware upgrading is supported (OTA) (*ESP32WROOM32D & ESP32WROOM32U Datasheet*, 2021).

BT Key Features:

Class-1, class-2, and class-3 transmitter without additional power amplifier, compliant with Bluetooth v4.2 BR/EDR and BLE requirements +12 dBm transmission power, enhanced power control Multi-connections in both traditional BT and Bluetooth Low Energy (BLE), Advertising and scanning in real time

Table 3.1 Arduino and ESP32 Comparison ("Arduino Buying Guide 2020," 2020)

Brand	Board	Processor	Clock Speed	GPIO/PWM	ADC/DAC	Internet	SD card slot	Dimensions	Price($)	Picture
Arduino	Uno wifi	8-bit ATMEGA4809	16 MHz	14/5	6/0	Wifi	-	68*54	45	
	Yun	8-bit ATmega32U4 + 16-bit Atheros AR9331	16 MHz + 400 MHz	20/7	12/0	Ethernet + Wifi	Yes	68*54	60	
NodeMCU	ESP8266	32-bit Xtensa Single-core	80 MHz	17/4	1/0	Wifi	-	49*25	8	
	ESP32	32-bit Xtensa Dual-Core	160 MHz	25/16	16/2	Wifi + BT V4	-	51*28	9	

The table above compares the ESP32 and other development cards used for similar purposes. When the table is examined, it is seen that ESP32 is both much faster and much cheaper. It also has wireless communication modules on its own ("Arduino Buying Guide 2020," 2020).

3.1.1.2. Texas Instruments ADS1299-x 24-Bit Analog-to-Digital Converters

The ADS1299 is an eight-channel, low-noise, 24-bit delta-sigma (ΔΣ) analog-to-digital converters (ADCs) with a built-in programmable gain amplifier (PGA), internal reference, and onboard oscillator. For extra cranial electroencephalography (EEG) and electrocardiography (ECG) applications, the ADS1299 has all of the characteristics that are usually required. The ADS1299 allows the design of scalable medical instrumentation systems because to its high degrees of integration and great performance (Texas Instruments Incorporated, 2012).

Figure 3.2 ADS1299 IC (Texas Instruments Incorporated, 2012)

Applications

Electroencephalogram (EEG) study, Sleep study monitor, Evoked Audio Potential (EAP), Bispectral Index (BIS), Fetal Electrocardiography (ECG).

3.1.1.3. Texas Instruments ADS1299EEGFE-PDK Performance Development Kit

The ADS1299EEGFE-PDK Performance Development Kit from Texas Instruments is a demonstration kit for the ADS1299. The ADS1299 is an eight-channel, 24-bit delta-sigma () analog-to-digital converter with simultaneous sampling (ADC). A programmable gain amplifier (PGA), an internal reference, and an inbuilt oscillator are all incorporated into this device. The ADS1299 has all of the functionality that electroencephalography (EEG) applications demand. The ADS1299EEGFE-PDK demonstration kit is designed to let you quickly evaluate and build your system (Rashid et al., 2018).

Hardware Features:

- Supply operation might be bipolar or unipolar.
- The internal and external clocks, as well as the reference, may be configured via jumper settings.
- It is possible to configure dc-coupled inputs.
- It is possible to provide a single reference to all channel negative terminals.
- As a reference electrode, any electrode can be utilized.
- As a bias electrode, any electrode can be utilized.
- On the exterior, there's a shield drive amplifier.

Software Features:

- The analytical tools offered include a virtual oscilloscope, histogram, and FFT.
- Export data for post-processing raw EEG data

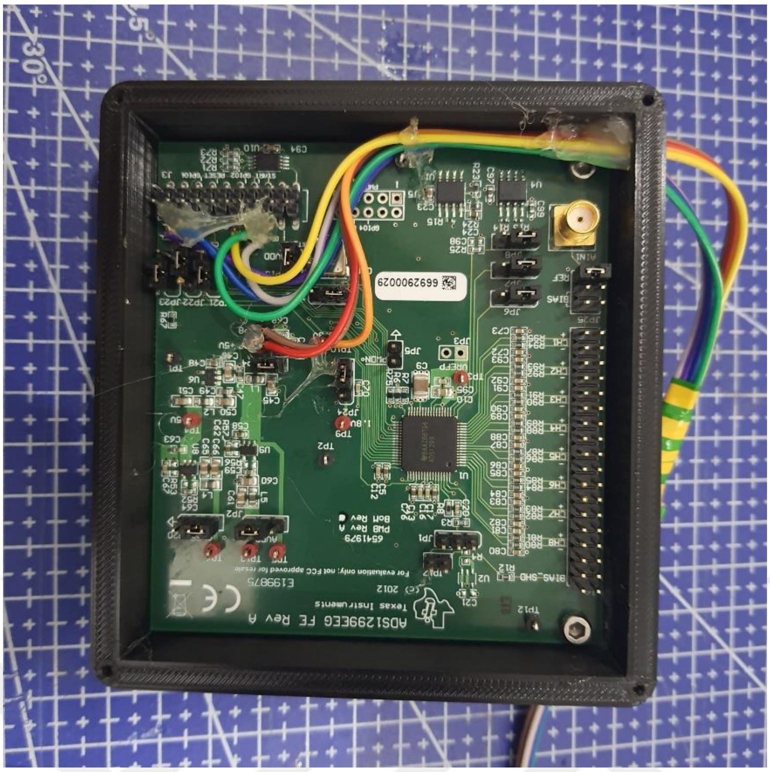

Figure 3.2 Texas Instruments ADS1299EEGFE-PDK Performance Development Kit used in Project

3.1.1.4. 18650 Lithium Battery Holder V8 Micro Usb

This module is a portable mobile power supply that supports two voltage outputs of 3V / 1A and 5V / 2.2A. 5V voltage output rated current 2.2A, supports maximum 3A current (not recommended for overload.), current output depends on the quality of 18650 battery. Micro USB charging current is 600mA. It supports two 18650 batteries. It is recommended to use two 18650 batteries.

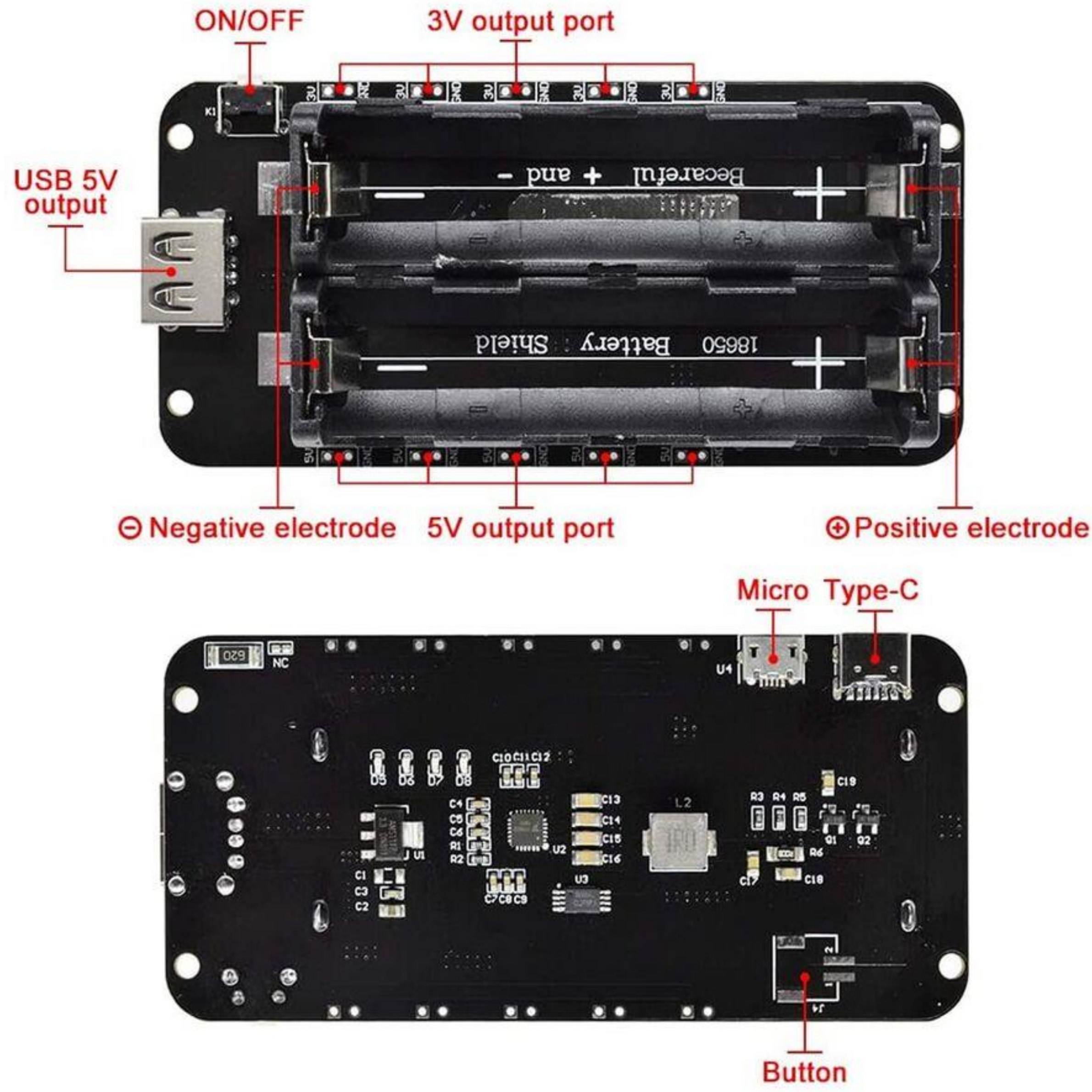

Figure 3.3 18650 Lithium Battery Holder

3.1.1.5. Sony Vtc6 18650 3.7V 3000 Mah Li-Ion Battery

Sony Vtc6 18650 3.7V 3000 Mah 2 Li-ion Rechargeable Battery. The usage areas of SONY VTC 6 can be listed as terminal battery, medical batteries, flashlight battery, notebook battery, electronic devices.

3.1.1.6. Dry EEG Comb Electrodes

For long-term comfort and wearability, the prongs of this dry EEG electrode finish in blunt ends. Longer hair may be accommodated by the expanded (5mm) prongs, which also provide great signal quality.

Figure 3.4 Dry EEG Comb Electrodes (*Dry EEG Comb Electrodes (Pack of 30)*, n.d.)

3.1.2. Mechanical Materials

The designed mechanical parts are generally manufactured using 3D printer technology. In the design process, designs that can be produced with 3D printers due to the production method were taken as basis and improvements and additions were made. Apart from the parts produced with a 3D printer, bolts and nuts were used to assemble the assembly parts.

3.1.2.1. Ultracortex Mark IV frame (Medium)

The Ultracortex is a 3D-printable open-source headsets that can be used with any OpenBCI Board. It can capture high-quality brain activity (EEG), muscle activity (EMG), and heart activity for research purposes (ECG). It isn't intended for use with transcranial stimulation. This headset is only for receiving EEG signals. Up to 16 channels of EEG may be sampled from up to 35 distinct 10-20 positions with the Ultracortex Mark IV.

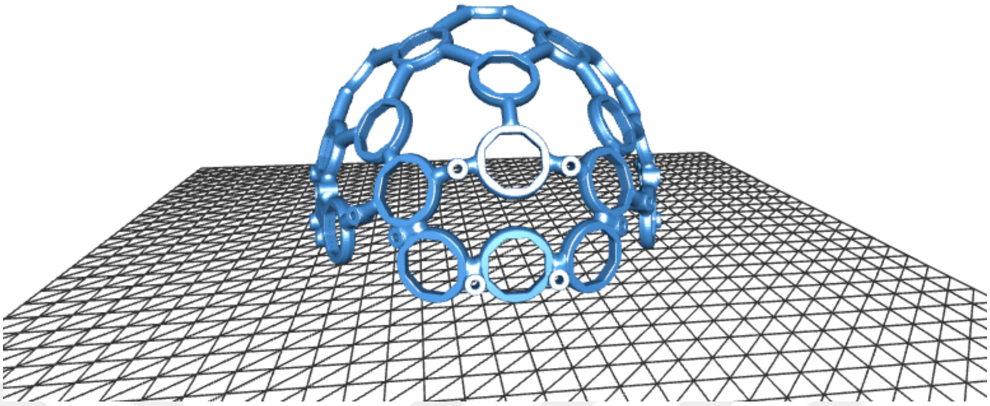

Figure 3.5 Front Part of Frame

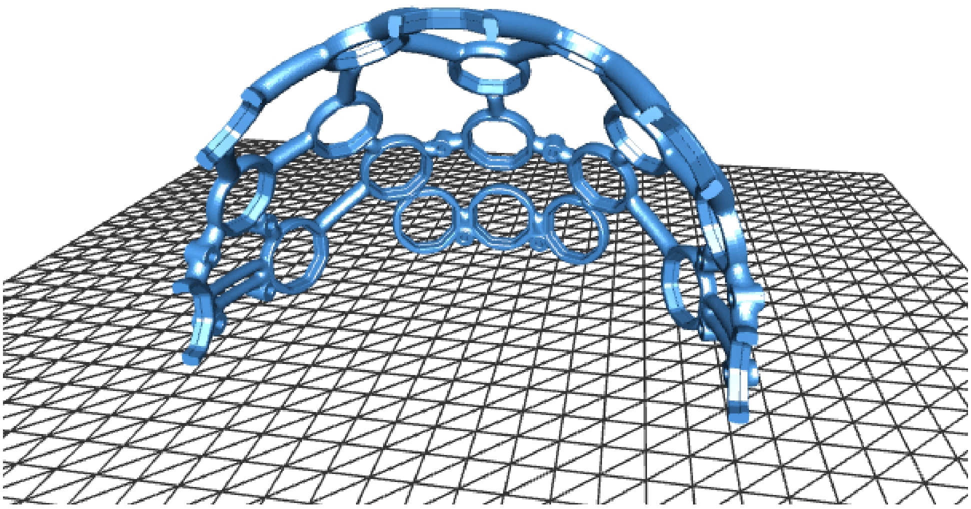

Figure 3.6 Backside Part of Frame

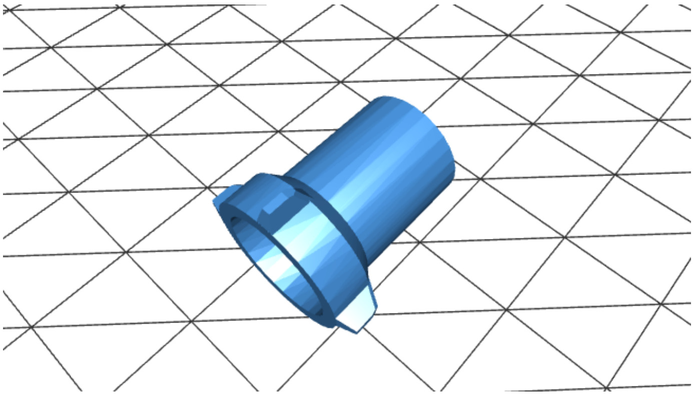

Figure 3.7 Electrode holder

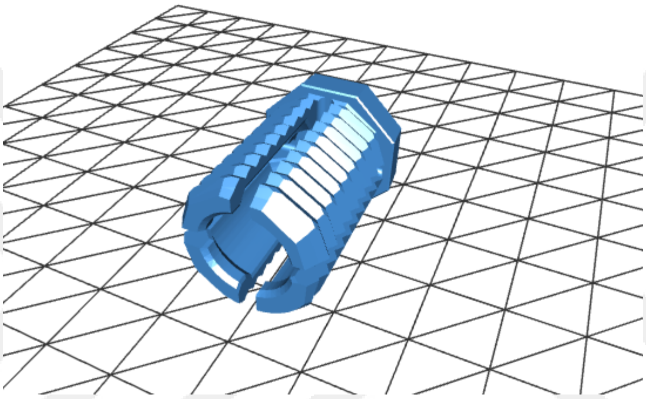

Figure 3.8 Octabolt

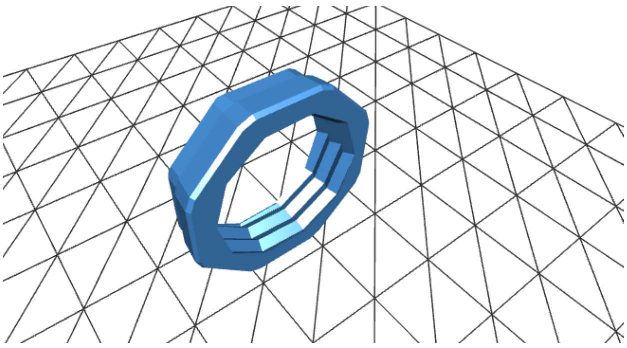

Figure 3.9 insert_105, dot5_percent Part

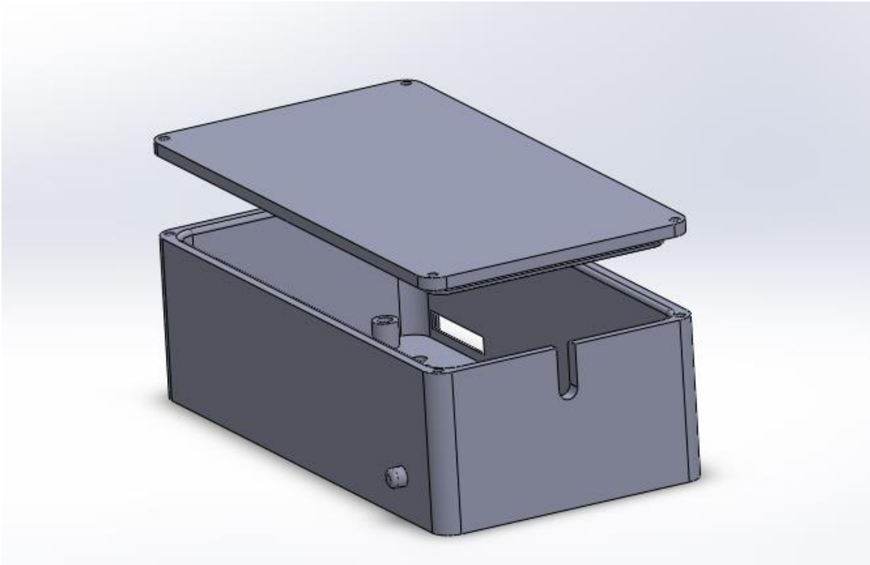

Figure 3.10 Battery Unit Box

The Power Unit Box in Figure 3.10 is designed in SolidWorks according to the size of the battery holder.

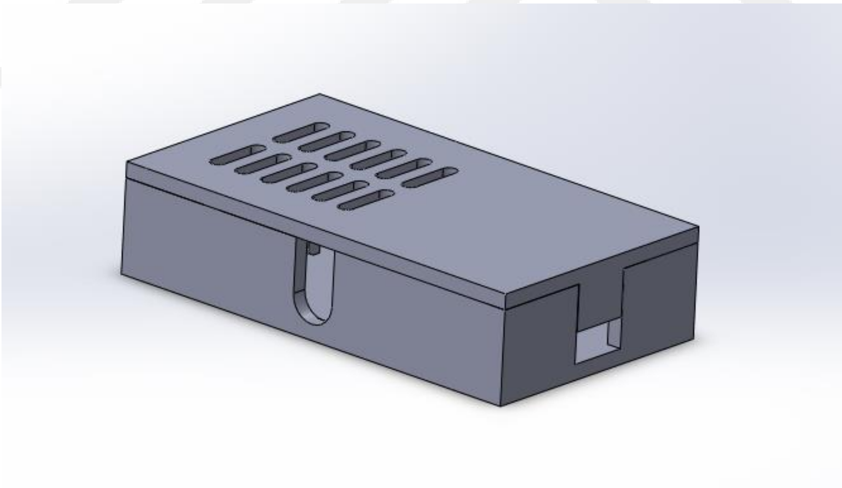

Figure 3.11 ESP32 Box

The ESP32 Box in Figure 3.11 is designed according to the size of the ESP32 DEV-KIT in SolidWorks.

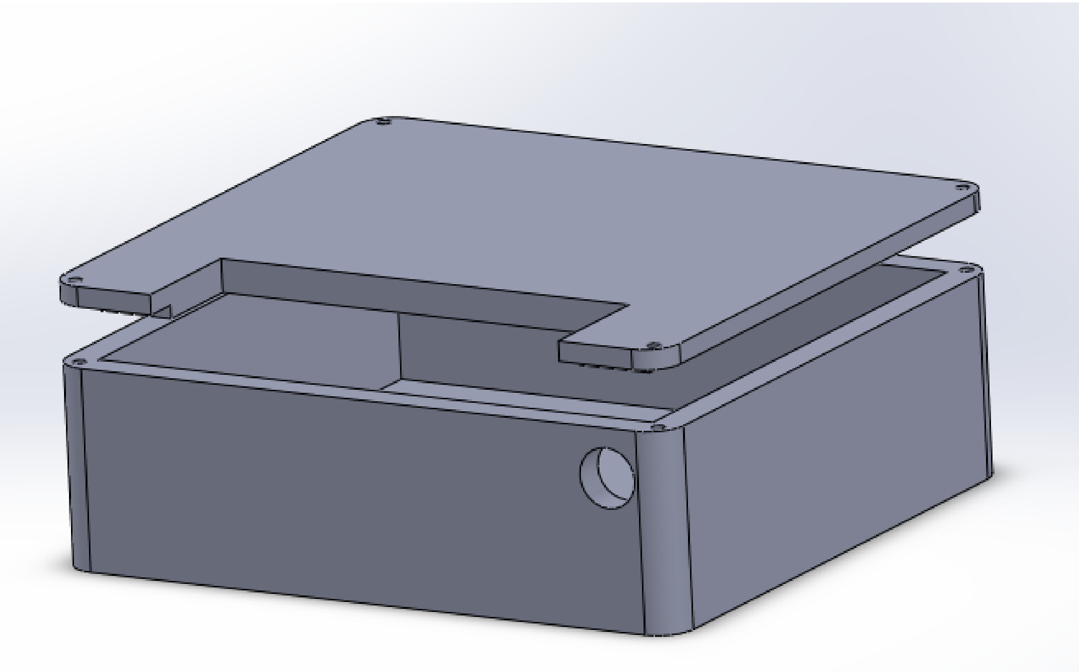

Figure 3.12 ADS1299EEGFE-PDK Performance Development Kit Box

This Box in Figure 3.11 is Designed in Solid Works according to dimension of ADS1299EEGFE-PDK.

3.2. The design and manufacturing of prototype system

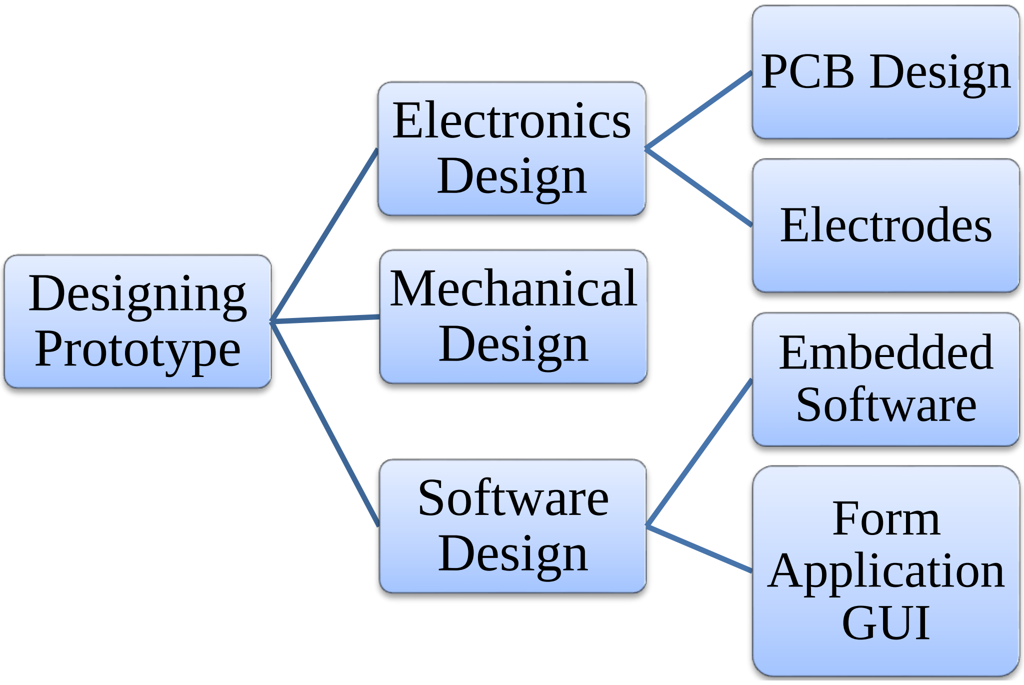

Figure 3.13 Design Scheme

3.2.1. Mechanical Design

One of the most important parts of the project is to design and manufacture the mechanical parts of an economic, robust, ergonomic portable device. For this reason, 3D printer technology, which is now easily accessible and could be made at a very low cost, has played a key role in this project in mechanical design and production as shown in the Figure 3.5-3.6. Since OpenBCI has already openly shared the cap and electrode designs they have designed for EEG devices, the design of the cap part of OpenBCI has been highly utilized in the mechanical design of this project (*Could OpenBCI Support Texas Instruments ADS1299EEGFE-PDK ?*, n.d.).

Apart from caps and electrodes: The power unit, the box of the ESP32 and the box of the ADS1299 development card are specially designed using the SolidWorks program as shown in the Figure 3.10-3,11-3.12, based on the dimensions of the devices. The advantages of 3D printer technology are as follows;

- Design that is adaptable
- Parts that are both durable and light
- Waste was minimized.
- Budget-friendly.
- Design and production should be completed quickly.
- Friendly to the environment

3.2.2. Software Design

The developed prototype has a two-stage software. These are; embedded software and graphical user interface.

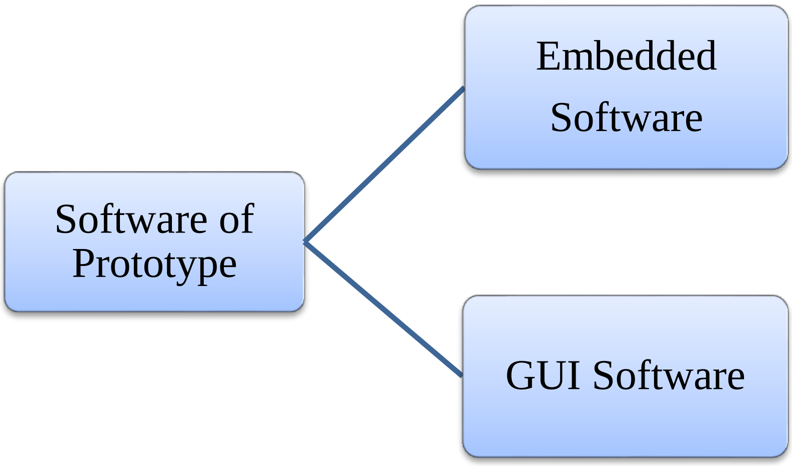

Figure 3.14 software design stages

Embedded software runs on the device's microcontroller. Embedded software is written for controling machines and non-computer devices. Embedded software is often customized for the hardware on which it will be run, and has time and memory constraints. The graphical user interface, on the other hand, is a general software used to express all the icons, windows, buttons and panels instead of the commands and their outputs operated on the computers of the device connected to the computer via Bluetooth and USB. The embedded software used in our project and the graphical user interface running on the computer are explained in detail below.

3.2.2.1. Embedded software

The main task of our device is to sensitively read the potential difference information received from the electrodes, to pass the received data through various filters, to transfer this collected data in the desired format to the computer using the serial communication protocol over Bluetooth, and to enable the commands sent via the serial communication protocol to be processed on the device by using the computer via Bluetooth. This is the purpose of the code running on the microcontroller on device.

Since the project was made to be a pioneer for developers and students, and in order to keep the cost low, the controller on which the embedded software was running was taken ready to use as a development board. The project must have a capacity to receive 250 samples per second from at least 8 channels and process them and be suitable for wireless communication. Considering all these, the ESP32 WROOM32D development board, which is discussed in detail in the material part, was chosen because it has both processor speed and wifi and Bluetooth communication modules on it, and most importantly, it is very affordable compared to its other counterparts.

The development board is supported by many IDEs, and installation and debug operations can be done through these IDEs. In order for the project to be easily used by developers and students, the embedded software has been developed on the Arduino IDE, which is easily accessible and used by many developers and students. In order to develop the software, 3rd party licensed libraries must be added to the Arduino IDE. How this is done is explained below.

Embedded Software highlights and key points

The ADS1299 integrated controller used in the project communicates with the SPI Protocol, so we need to add the SPI library to our software. In addition, since the device will communicate with the computer via Bluetooth, the Bluetooth library must be added.

In order to use ADS1299, various SPI commands written in the data sheet of the integrated circuit are needed. A library with these definitions should also be added to the software.

Table 3.2 ADS1299 Command List (Texas Instruments Incorporated, 2012)

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]

Table 3.3 ADS1299 Register Settings (Texas Instruments Incorporated, 2012)

ADDRESS	REGISTER	RESET VALUE (Hex)	BIT 7	BIT 6	BIT 5	BIT 4	BIT 3	BIT 2	BIT 1	BIT 0
Device Settings (Read-Only Registers)										
00h	ID	00	REV_ID3	REV_ID2	REV_ID1	1	DEV_ID2	DEV_ID1	NU_CH2	NU_CH1
Global Settings Across Channels										
01h	CONFIG1	96	1	DAISY_EN	CLK_EN	1	0	DR2	DR1	DR0
02h	CONFIG2	C0	1	1	0	INT_CAL	0	CAL_AMP0	CAL_FREQ1	CAL_FREQ0
03h	CONFIG3	60	PD_REFBUF	1	1	BIAS_MEAS	BIASREF_INT	PD_BIAS	BIAS_LOFF_SENS	BIAS_STAT
04h	LOFF	00	COMP_TH2	COMP_TH1	COMP_TH0	0	ILEAD_OFF1	ILEAD_OFF0	FLEAD_OFF1	FLEAD_OFF0
Channel-Specific Settings										
05h	CH1SET	61	PD1	GAIN12	GAIN11	GAIN10	SRB2	MUX12	MUX11	MUX10
06h	CH2SET	61	PD2	GAIN22	GAIN21	GAIN20	SRB2	MUX22	MUX21	MUX20
07h	CH3SET	61	PD3	GAIN32	GAIN31	GAIN30	SRB2	MUX32	MUX31	MUX30
08h	CH4SET	61	PD4	GAIN42	GAIN41	GAIN40	SRB2	MUX42	MUX41	MUX40
09h	CH5SET	61	PD5	GAIN52	GAIN51	GAIN50	SRB2	MUX52	MUX51	MUX50
0Ah	CH6SET	61	PD6	GAIN62	GAIN61	GAIN60	SRB2	MUX62	MUX61	MUX60
0Bh	CH7SET	61	PD7	GAIN72	GAIN71	GAIN70	SRB2	MUX72	MUX71	MUX70
0Ch	CH8SET	61	PD8	GAIN82	GAIN81	GAIN80	SRB2	MUX82	MUX81	MUX80
0Dh	BIAS_SENSP	00	BIASP8	BIASP7	BIASP6	BIASP5	BIASP4	BIASP3	BIASP2	BIASP1
0Eh	BIAS_SENSN	00	BIASN8	BIASN7	BIASN6	BIASN5	BIASN4	BIASN3	BIASN2	BIASN1
0Fh	LOFF_SENSP	00	LOFFP8	LOFFP7	LOFFP6	LOFFP5	LOFFP4	LOFFP3	LOFFP2	LOFFP1
10h	LOFF_SENSN	00	LOFFM8	LOFFM7	LOFFM6	LOFFM5	LOFFM4	LOFFM3	LOFFM2	LOFFM1
11h	LOFF_FLIP	00	LOFF_FLIP8	LOFF_FLIP7	LOFF_FLIP6	LOFF_FLIP5	LOFF_FLIP4	LOFF_FLIP3	LOFF_FLIP2	LOFF_FLIP1
Lead-Off Status Registers (Read-Only Registers)										
12h	LOFF_STATP	00	IN8P_OFF	IN7P_OFF	IN6P_OFF	IN5P_OFF	IN4P_OFF	IN3P_OFF	IN2P_OFF	IN1P_OFF
13h	LOFF_STATN	00	IN8M_OFF	IN7M_OFF	IN6M_OFF	IN5M_OFF	IN4M_OFF	IN3M_OFF	IN2M_OFF	IN1M_OFF
GPIO and OTHER Registers										
14h	GPIO	0F	GPIOD4	GPIOD3	GPIOD2	GPIOD1	GPIOC4	GPIOC3	GPIOC2	GPIOC1
15h	MISC1	00	0	0	SRB1	0	0	0	0	0
16h	MISC2	00	0	0	0	0	0	0	0	0
17h	CONFIG4	00	0	0	0	0	SINGLE_SHOT	0	PD_LOFF_COMP	0

WREG FUNCTION:

```
void WREG(byte _address, byte _value) {
  byte opcode1 = _WREG + _address; //001rrrrr; _RREG = 00100000 and _address
= rrrrr
  digitalWrite(CS, LOW); //Low to communicated
  SPI.transfer(_SDATAC); //SDATAC
  SPI.transfer(opcode1);
  SPI.transfer(0x00);
  SPI.transfer(_value);
  SPI.transfer(_RDATAC);
  digitalWrite(CS, HIGH); //Low to communicated
  //  Serial.print("Register 0x");
  //  Serial.print(_address, HEX);
  //  Serial.println(" modified.");
  SerialBT.print("Register 0x");
  SerialBT.print(_address, HEX);
  SerialBT.println(" modified.");
}
```

WREG Function is the function responsible for writing the configuration registers on the ADS1299. It writes data to registers using SPI communication (Feuer, 2013/2021).

RREG FUNCTION:

```
void RREG(byte _address, byte _numRegistersMinusOne) {
  byte opcode1 = _RREG + _address; //001rrrrr; _RREG = 00100000 and _address
= rrrrr
  digitalWrite(CS, LOW); //Low to communicated
  SPI.transfer(_SDATAC); //SDATAC
  SPI.transfer(opcode1); //RREG
  SPI.transfer(_numRegistersMinusOne); //opcode2
  for (byte i = 0; i <= _numRegistersMinusOne; i++) {
    byte data = SPI.transfer(0x00); // returned byte should match default of
register map unless previously edited manually (Datasheet, pg.39)
    printRegisterName(i);
    //Serial.print("0x");
    SerialBT.print("0x");
    if (i < 16) Serial.print("0"); //lead with 0 if value is between 0x00-
0x0F to ensure 2 digit format
    //    Serial.print(i, HEX);
    //    Serial.print(", ");
    //    Serial.print("0x");
    SerialBT.print(i, HEX);
    SerialBT.print(", ");
    SerialBT.print("0x");
    if (data < 16) Serial.print("0"); //lead with 0 if value is between 0x00-
0x0F to ensure 2 digit format
    //    Serial.print(data, HEX);
    //    Serial.print(", ");
    SerialBT.print(data, HEX);
    SerialBT.print(", ");
    for (byte j = 0; j < 8; j++) {
      //Serial.print(bitRead(data, 7 - j), BIN);
      SerialBT.print(bitRead(data, 7 - j), BIN);
      if (j != 7) //Serial.print(", ");
        SerialBT.print(", ");
    }
    //Serial.println();
    SerialBT.println();
  }
  SPI.transfer(_RDATAC); //turn read data continuous back on
  digitalWrite(CS, HIGH); //High to end communication
}
```

The RREG function is a function used to read the data recorded in the registers at the desired address from the registers on the ADS1299. It reads data from addresses using SPI communication (Feuer, 2013/2021).

CONFIGURATION ADS1299:

```
    //Write register command (see Datasheet pg. 38 for more info about WREG)
    WREG(CONFIG1, 0x96);
    delay(5);
    WREG(CONFIG2, 0xD0);
    delay(5);
    WREG(CONFIG3, 0XFC);//0XE0 for test 0xE1 for EEG 250sps 0XFC
    delay(5);
    WREG(CONFIG4, 0x02);//0x02 for lead off detection on
```

```
    delay(5);
    WREG(LOFF_SENSP, 0xFF);//0xFF for lead off detection on
    delay(5);
    WREG(MISC1, 0x20);
    delay(5);
    WREG(LOFF, 0x00);


    for (int _channel = 1; _channel < 9; _channel++ )
      WREG(CH1SET + (_channel - 1), 0x00); //0x65 for test 0x00 normal
electrode
```

The ADS1299 can be configured in many different ways. For example; reference settings, sampling rate per second, whether lead off detection is on, whether it is in test mode or active mode, and many more settings can be changed by writing data to the registers given in Table 3.2 and 3.3. This part of the program writes data to registers for configuration as used in our project.

READ CONTUNIOUS DATA:

```
void updateData() {
  if (digitalRead(DRDY) == LOW) {
    digitalWrite(CS, LOW);
    long output[9];
    long dataPacket;
    for (int i = 0; i < 9; i++) {
      for (int j = 0; j < 3; j++) {
        byte dataByte = SPI.transfer(0x00);
        dataPacket = (dataPacket << 8) | dataByte;
      }
      output[i] = dataPacket;
      dataPacket = 0;
    }
    digitalWrite(CS, HIGH);

    if (xSemaphoreTake(timerSemaphore, 0) == pdTRUE) {

      SerialBT.print("<C>,");
// IMPORTAND FOR CONVERT DATA 24 BIT TO INTEGER
      for (int i = 1; i < 9; i++) {
        if (output[i] & 0x00800000) // if bit 23 of ConversionData[i] is 1
        {
          output[i] |= 0xFF000000;
        }
        else
        {
          output[i] &= 0x00FFFFFF;
        }

// IMPORTAND END-----------------------------------

        SerialBT.print((float)output[i]*SCALE_FACT, 0);
        if (i != 8) {
```

```
                SerialBT.print(", ");
              }

            }
            SerialBT.println();

            outputCount++;
          }
        }
      }
```

Another feature of ADS1299 is to read data continuously and by sending a request. The updateData Function receives the data sent from ADS1299 continuously according to the amount of data sent per second programmed in the continuous data reading mode, using SPI communication and assigns it to the necessary variables (Feuer, 2013/2021).

READ SERIAL COMMAND:

```
void ReadSerial() {
  int i = 0;
  while (SerialBT.available() > 0) {
    char aChar = SerialBT.read();

    if (aChar == '<') {
      started = true;
      ended = false;
    }
    else if (aChar == '>') {
      ended = true;
      break; // break the while loop
    }
    else {
      buff[i] = aChar;
      i++;
      buff[i] = '\0'; // this terminates the array
    }
  }

  if (started && ended) {
    //   int intpos;
    //   char pos[3] = { buff[1], buff[2], buff[3] };
    //   intpos = atoi(pos);
    if (buff[0] == 'U') {
      startedLogging = true;
      Serial.print("startedLogging");
    }
    else if (buff[0] == 'D')
      startedLogging = false;
    else if (buff[0] == 'S') {
      Serial.print("devicestarted");
      starteddevice = true;
    }
    else if (buff[0] == 'L')
      readleadoffstatus = true;

    i = 0;
    buff[i] = '\0'; // this terminates the array
```

```
      started = false;
      ended = false;
    }
}
```

The ReadSerial function receives and executes the commands sent to the device via serial communication from the interface.

TIMER INTERRUPT:

Timer interrupt was used to reduce the 250 sample rate to 128.

```
void IRAM_ATTR onTimer() {
  portENTER_CRITICAL_ISR(&timerMux);
  portEXIT_CRITICAL_ISR(&timerMux);
  xSemaphoreGiveFromISR(timerSemaphore, NULL);

}
  timer = timerBegin(0, 80, true);

  // Attach onTimer function to our timer.
  timerAttachInterrupt(timer, &onTimer, true);

  // Set alarm to call onTimer function every second (value in microseconds).
  // Repeat the alarm (third parameter)
  timerAlarmWrite(timer, 7812, true);//7812
```

3.2.2.2. Graphical User Interface (GUI)

The graphical user interface is a general software used to express all the icons, windows, buttons and panels of the device connected to the computer via Bluetooth and USB, instead of the commands and their outputs operated on the computers. A graphical application running on the computer is required to control the device, to see the data sent to the computer on the graph, to save the received data without loss, so that all users can use the device easily.

The required program for the prototype is written in C# (C-Sharp) Programming language using Visual Studio 2019 IDE. This program can only run on Windows7 and above Windows OS. The screenshot of the program and the functions of its sections are shown in the Figure 3.15.

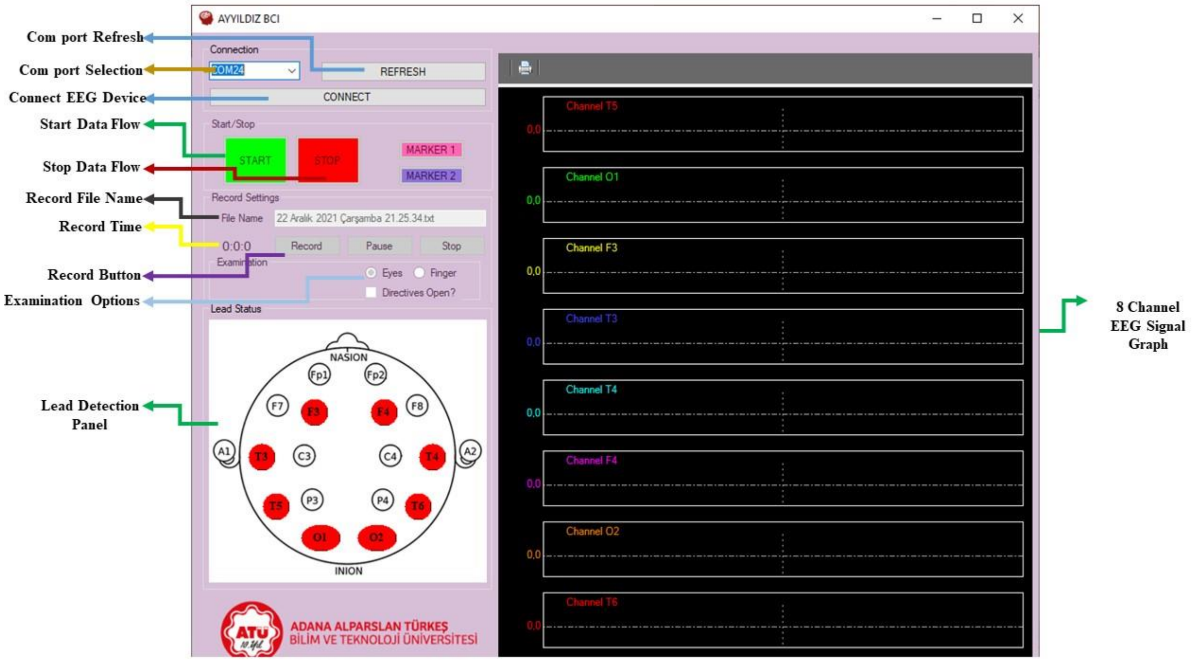

Figure 3.15 GUI screen

The program includes sections not only for controlling the device and recording the incoming data, but also for performing some simple experiments. In this way, it provides convenience to its users. The program sees and lists the serial port connections created by the EEG Device that is paired with a Bluetooth device already integrated into the computer or connected later. From the listed COM ports, the COM port to which the relevant device is connected is selected and the connection is established. Once the connection is established, the device is ready to send data. By pressing the start button, the data flow is started. Incoming data at this stage is displayed on the graph screen. The buttons are shown in Figure 3.15. If there is current between the electrodes and the reference, the red lead detection indicators will turn green as shown in Figure 3.16-3,17. A green indicator indicates that the electrode is in contact with the skin. In this way, the electrodes that do not touch the skin can be seen and intervened.

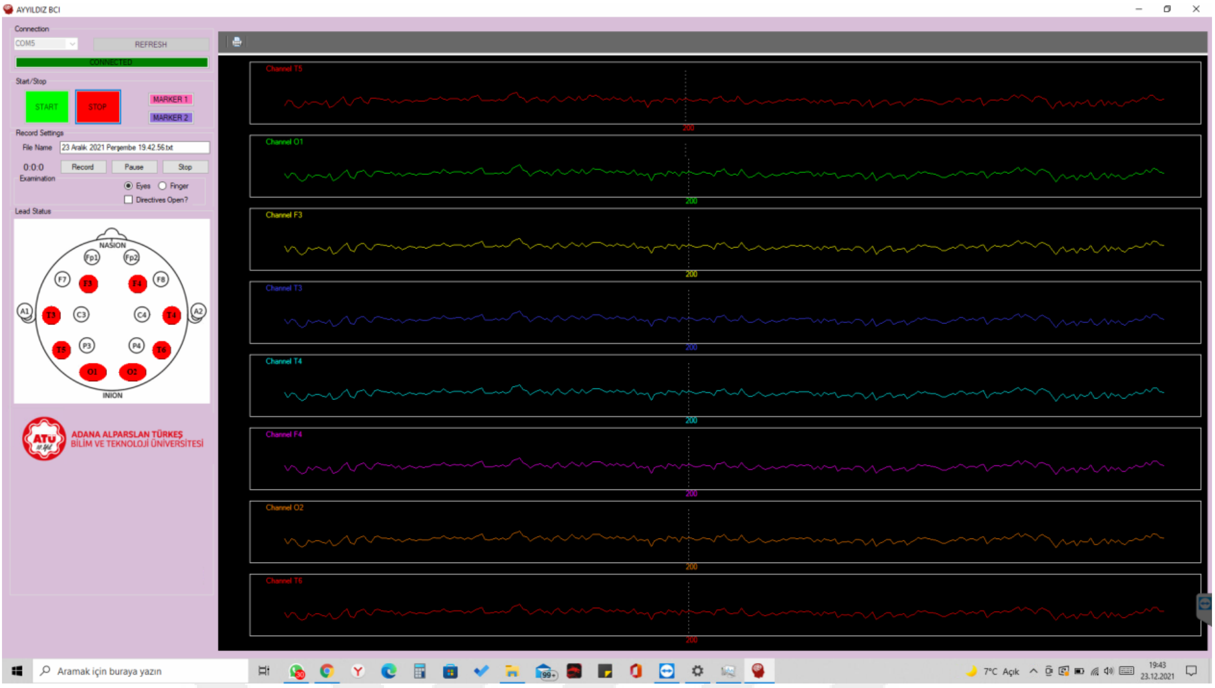

Figure 3.16 GUI example with electrodes not in contact

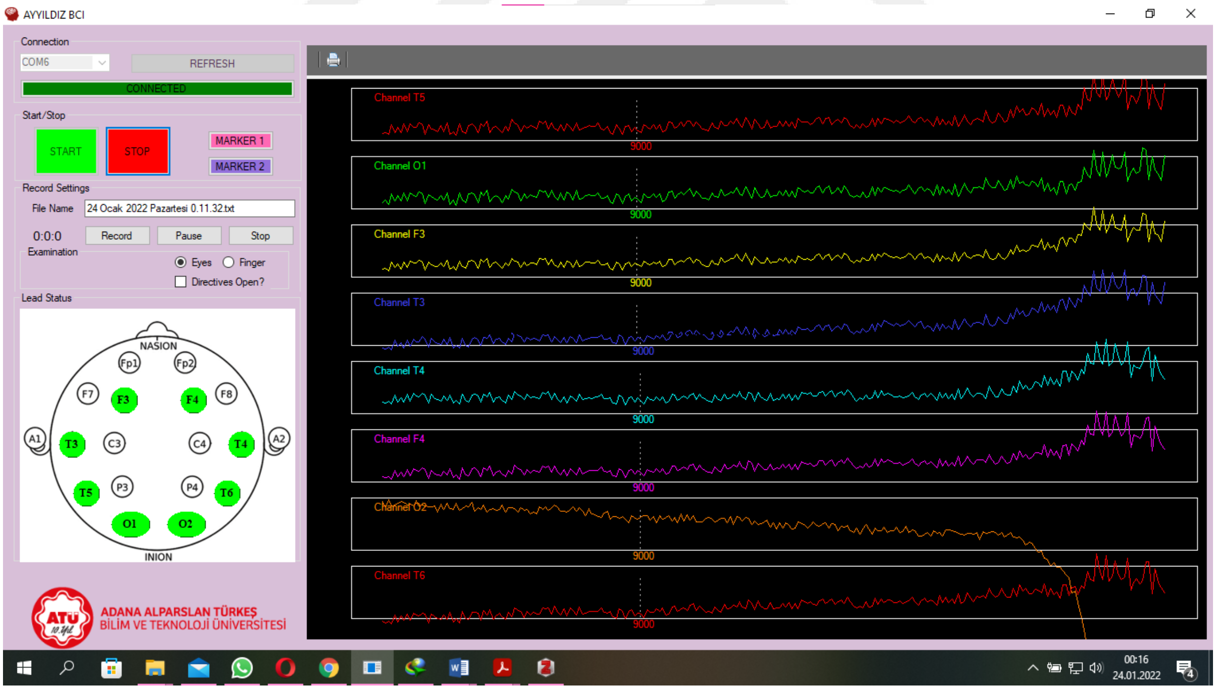

Figure 3.17 GUI example with electrodes in contact

Some important functions and key points are described below.

Graphics Library

A flowing graph is needed to properly display EEG Signals. As a result of the research, an open source graphics library was chosen in order not to bring extra cost to commercial graphics libraries. The said graphics library has been developed for ECG application and has been modified to make it suitable for displaying EEG signals. Developed by a programmer named Zimmermann Stephan, this library is licensed under The Code Project Open License (CPOL) open source license. The cost of the program has been reduced by using this library. A view from the demo application of the library is seen in the Figure 3.18.

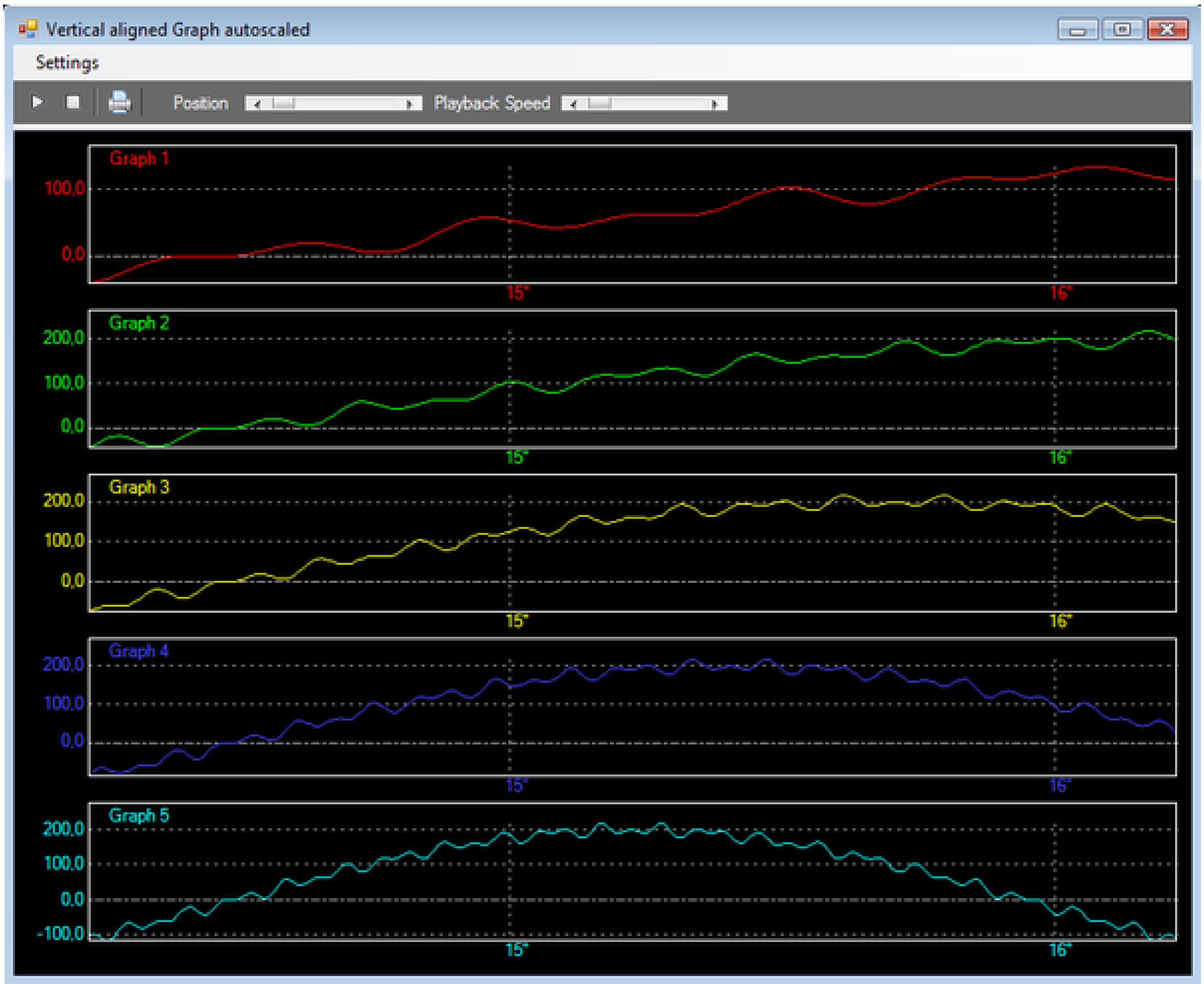

Figure 3.18 Graphic Library Demo Screen

This library adapts to variable ranges of the graphic by automatic sizing.

Multi-threding and parallel programming

A single loop is not enough to receive the high-speed data stream, process it, draw a graph and save it to a file. Therefore, by creating multiple loops, data is quickly received, processed and converted into graphics by exchanging data among themselves.

```
if (!readThread.IsAlive)
 {
   readThread.Name = "serial_read_thrad";
   readThread.Start();
  }

Thread plotThread = new Thread(Plot_graph);
 if (!plotThread.IsAlive)
  {
   plotThread.Name = "plot_thread";
   plotThread.Start();

    }
```

In this way, the performance of the program has been increased.

3.2.3. Electronics Design

While developing the prototype, the focus was primarily on the software. For this reason, a development and trial card specially produced for ADS1299 was obtained from Texas Instrument, the manufacturer of the ADS1299 IC. Software developments and debugging were made on this card. This card is not used in the current prototype, but an original EEG measuring device has been made ready for production thanks to the information gained due to the development card.

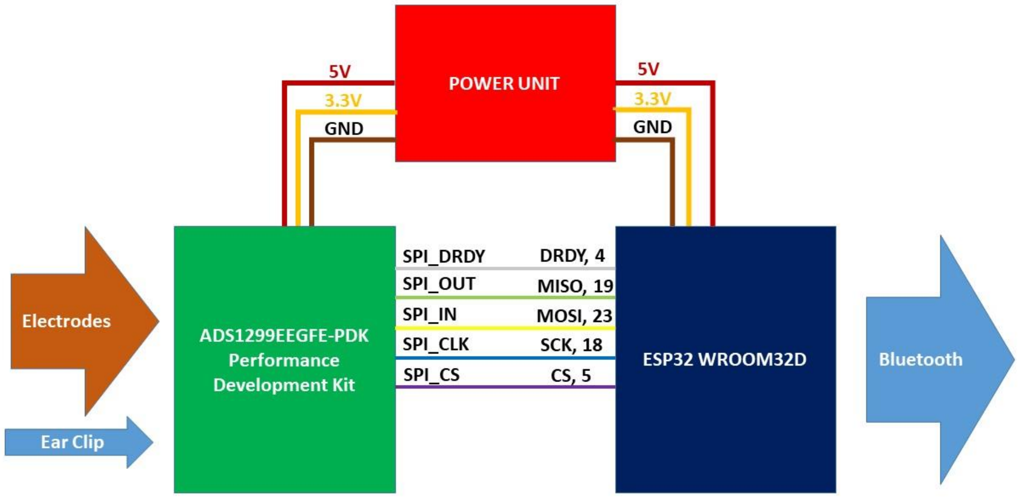

Figure 3.19 Electrical Connection Scheme

In the production of the first prototype, PCB design was not done, and a prototype was prepared with development cards in order to save time and cost. The electrical connection diagram is as in the Figure 3.19.

The power unit includes two 18650 type 3000mah 3.6 Volt li-ion batteries. There are micro USB C-type USB charging input ports on the power section. The charging module, to which the batteries are connected, has a battery management system on it. In this way, the batteries are protected against overcharge and discharge. The battery module provides 5 volts and 3.3 volts output. A maximum of 3 Ampere current can be drawn from these outputs. Thanks to a button on the battery module, the device can be turned on and off. A short press on the button turns it on, a long press for 3 seconds turns off the device.With a green LED indicator attached to the power unit, it can be seen whether the device is working or not.

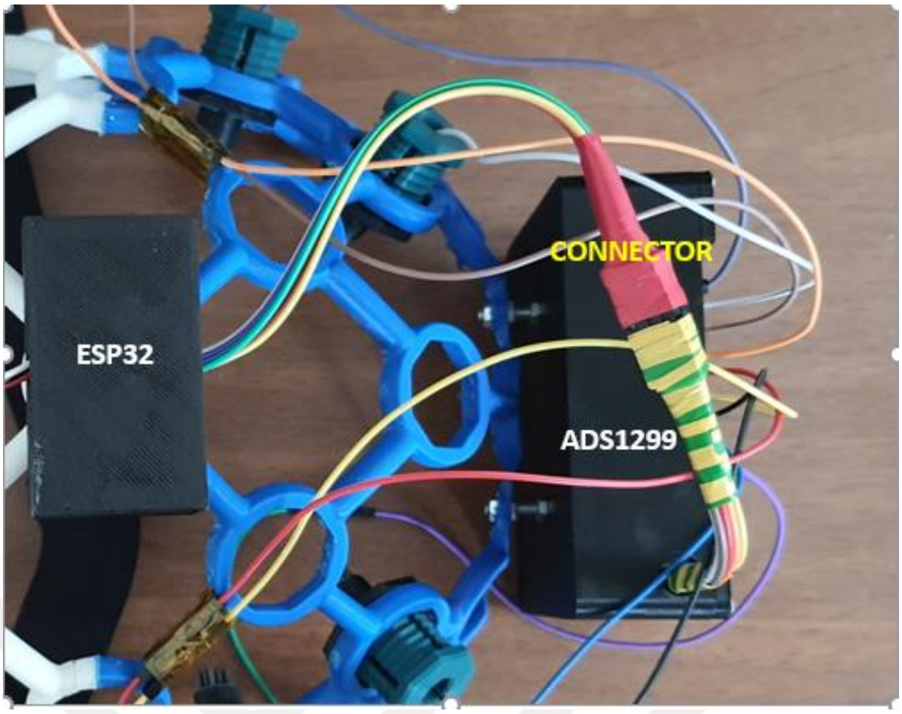

Figure 3.20 Connector view

ESP32 and ADS1299 modules are connected to each other by connector as shown in the Figure 3.21 so that they can be separated in one bit when necessary.

3.2.3.1. Electrodes

Dry type electrode is used as the electrode. Due to the structure of the electrode, skin contact can also be achieved on the scalp. In addition, since the surface of the electrode is coated with AgCl, the impedance between the skin and the electrode can be minimized. The design of the EEG cap was inspired by the cap of OpenBCI company. Dry electrodes that shown in the Figure 3.22 were also supplied from this company. 3D drawings shared as open source have been made suitable for this project by making minor changes. Normally, the electrode holders shown in the Figure 3.7-3.8-3.9 produced by the company with plastic injection were also printed on a 3D printer, just like the cap.

Figure 3.21 Dry Electrodes

Figure 3.22 Dry Electrode with Holder

Figure 3.23 Disassembly of Electrode Holder

Dry-type electrodes are attached to each other with a round-tipped cable lug with a stainless metric 2mm bolt and nut, and an electrode cap is obtained as shown in the Figure 3.24 . In this way, all electrodes were able to make good contact with the scalp.

The cables coming out of the electrodes are attached to the positive index pins on the ADS1299 board. In addition, the ear clip, which is used as a reference, was also printed with a 3D printer and a dry electrodes were used. The reference electrode shown in the Figure 3.25 is also connected to the SRB1 pin on the board.

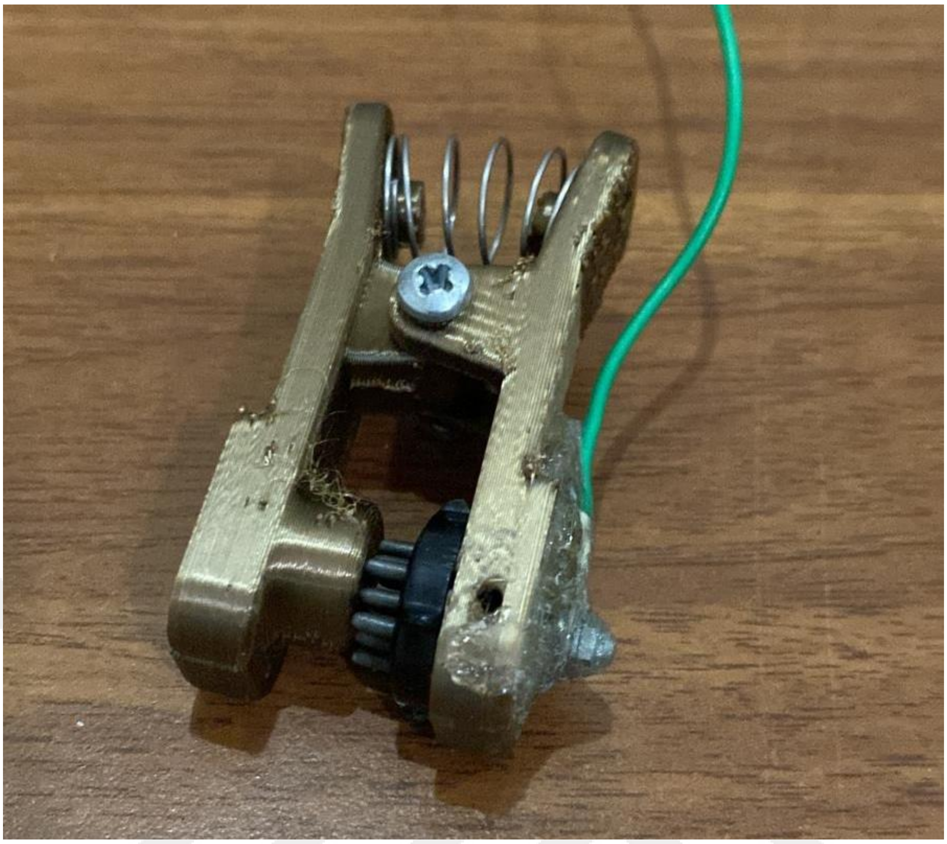

Figure 3.24 Ear reference Clip

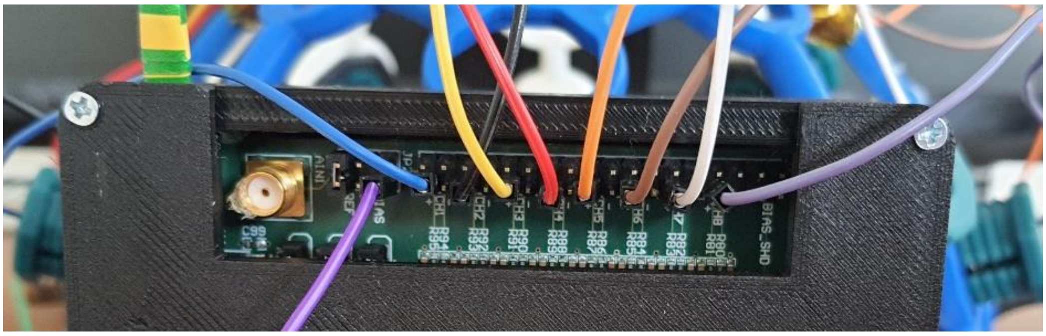

Figure 3.25 Connection with Electrodes and ADS1299 Board

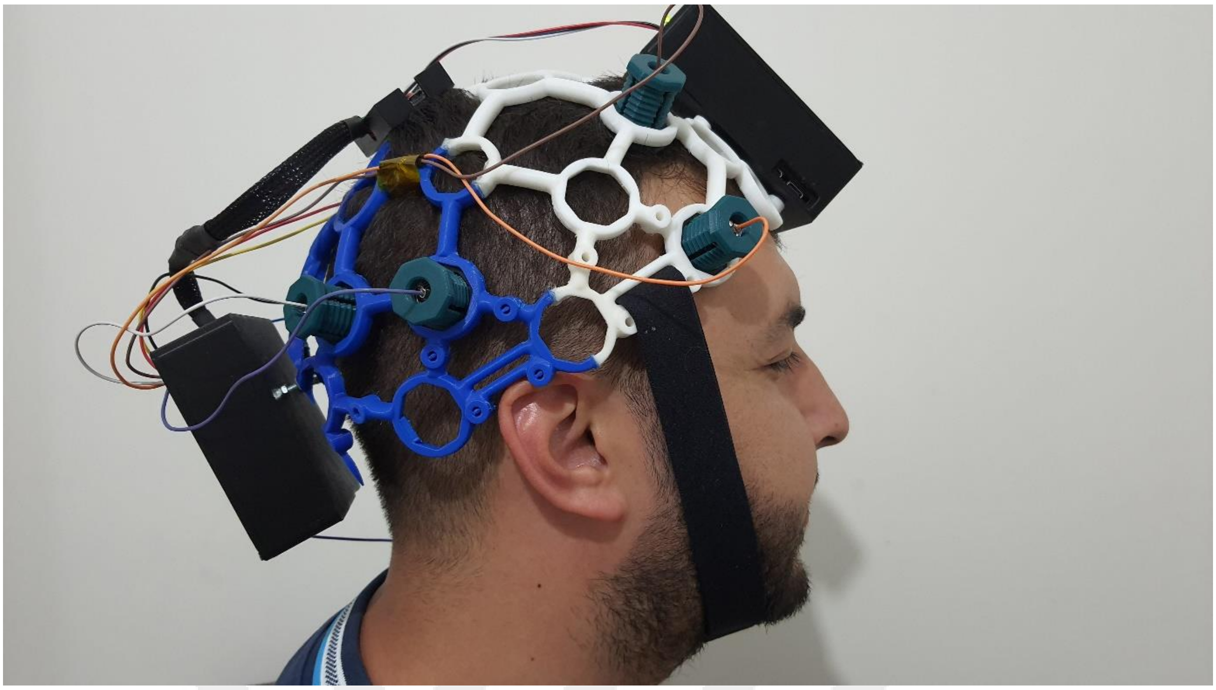

Figure 3.26 Side view of Prototype

All modules are boxed separately as shown in the Figure 3.27. There are two important reasons for this;

- They do not make electrical noise and affect each other's signal.
- Ensuring the weight balance on the front and back of the cap.

3.2.3.2. Unique PCB design

The first prototype produced using the ADS1299 FDK development board. This provided the experience needed to design a unique PCB. In the light of the information obtained, a low-cost card design that is open to development with the desired features has been made. The important parts of the card's scheme are below.

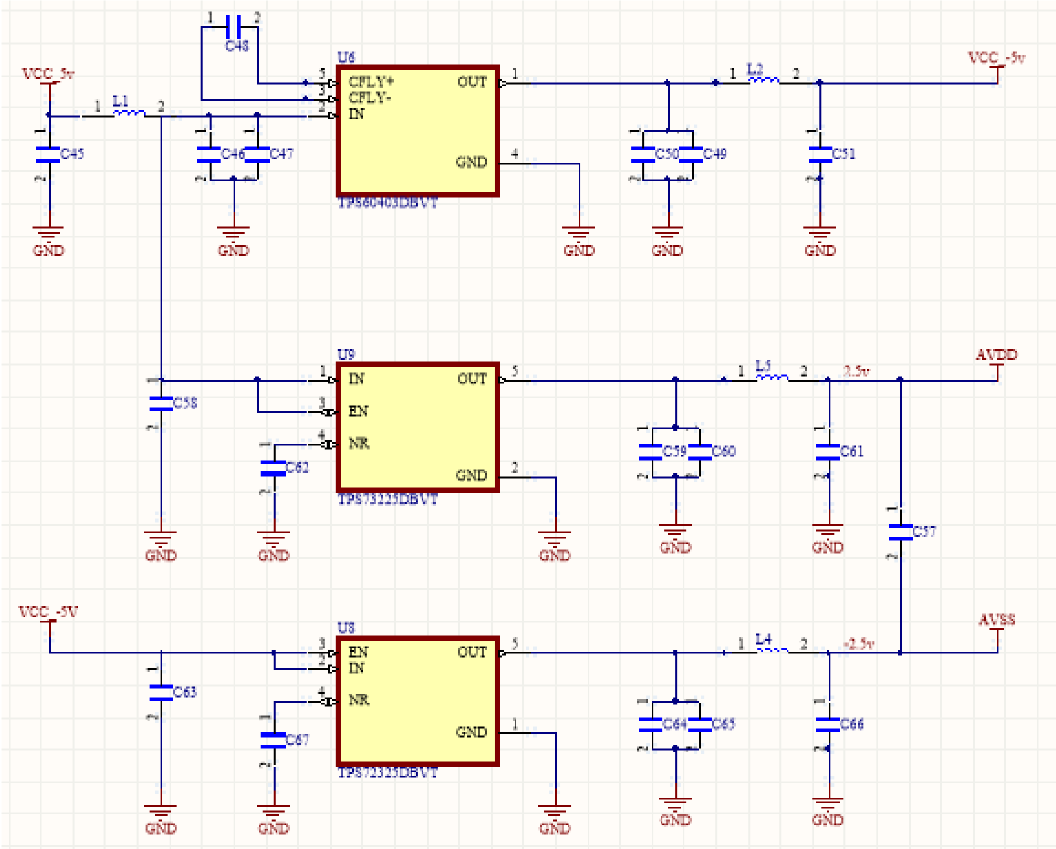

Figure 3.27 Power ICs of board

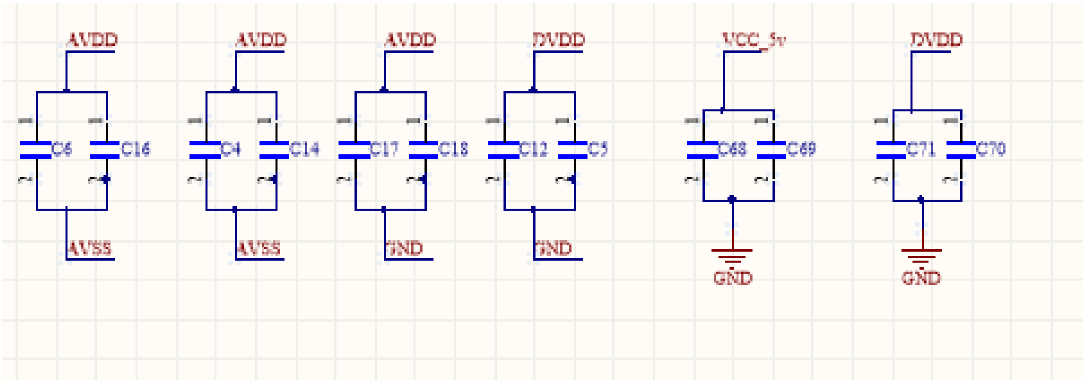

Figure 3.28 Power Capacitors

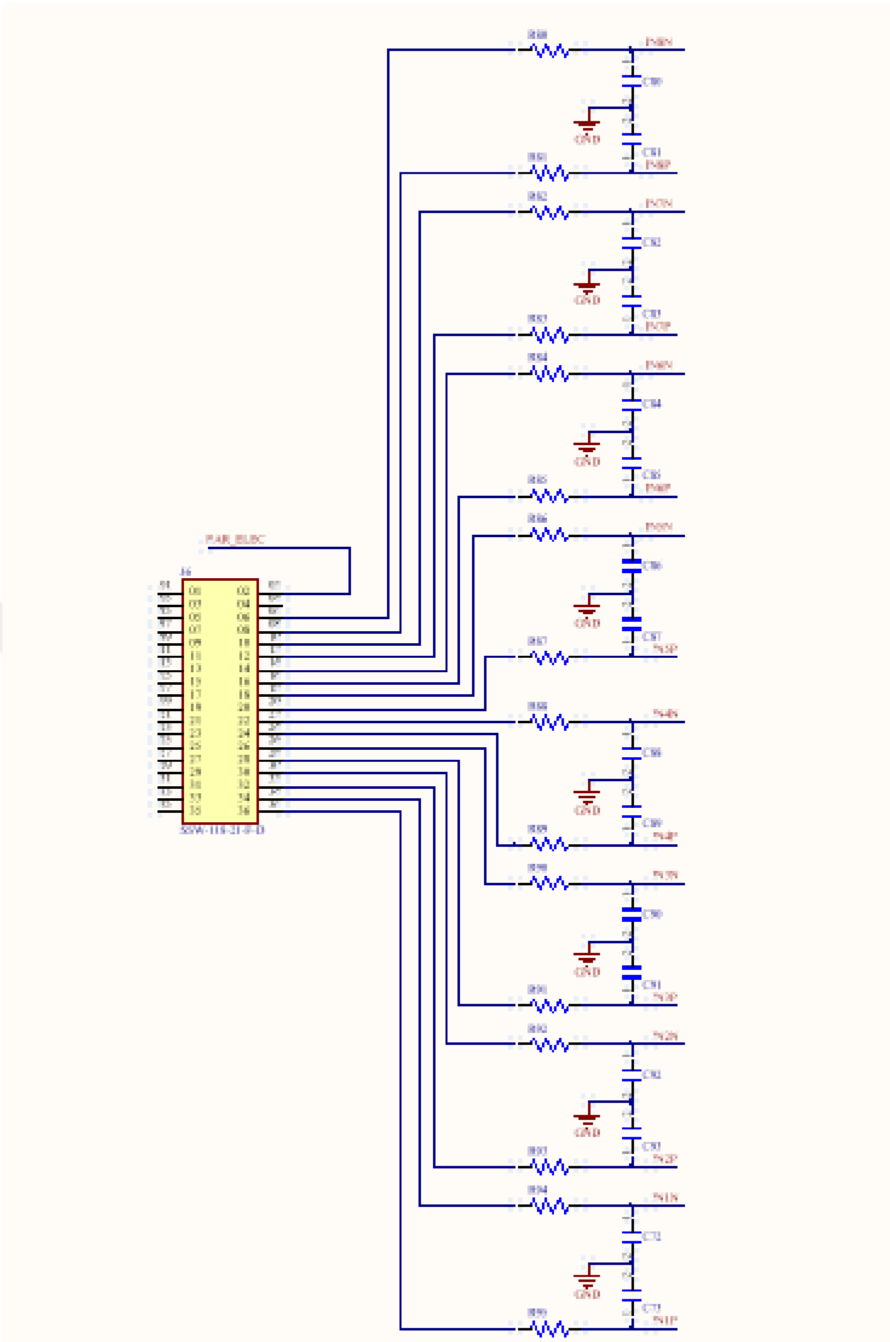

Figure 3.29 Electrode Input Connector and Low Pass Filter

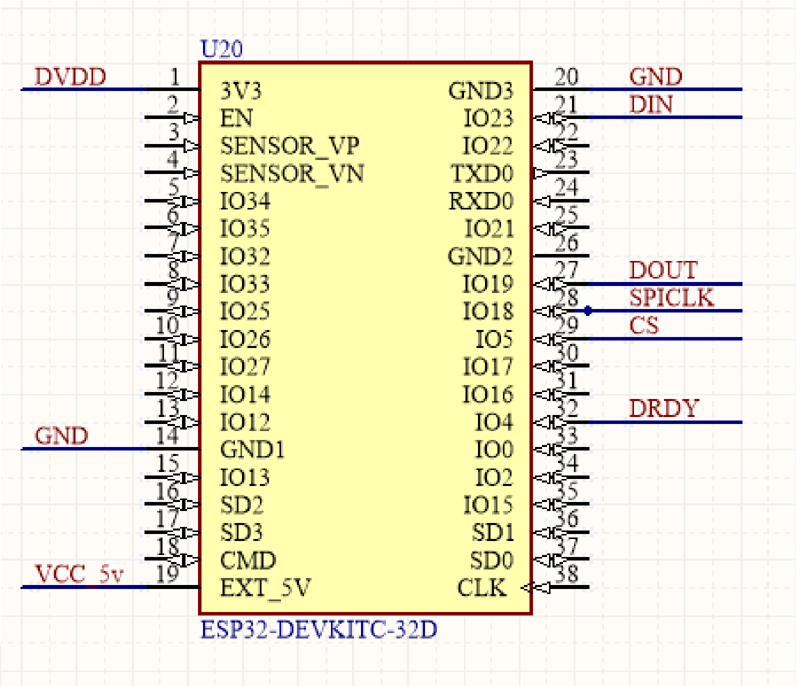

Figure 3.30 ESP32 and Connection

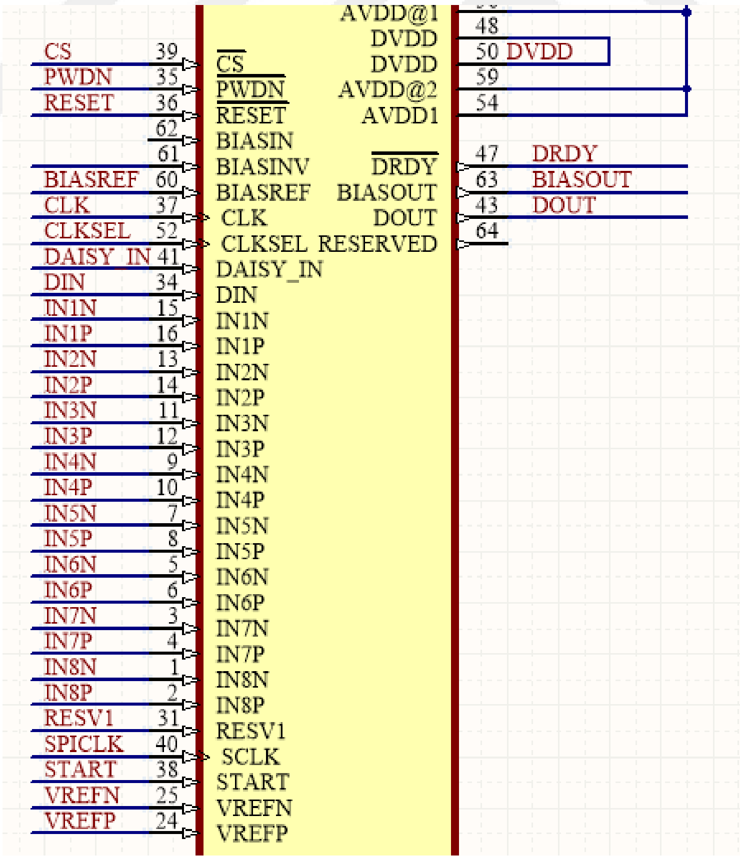

Figure 3.31 ADS1299 and Connections

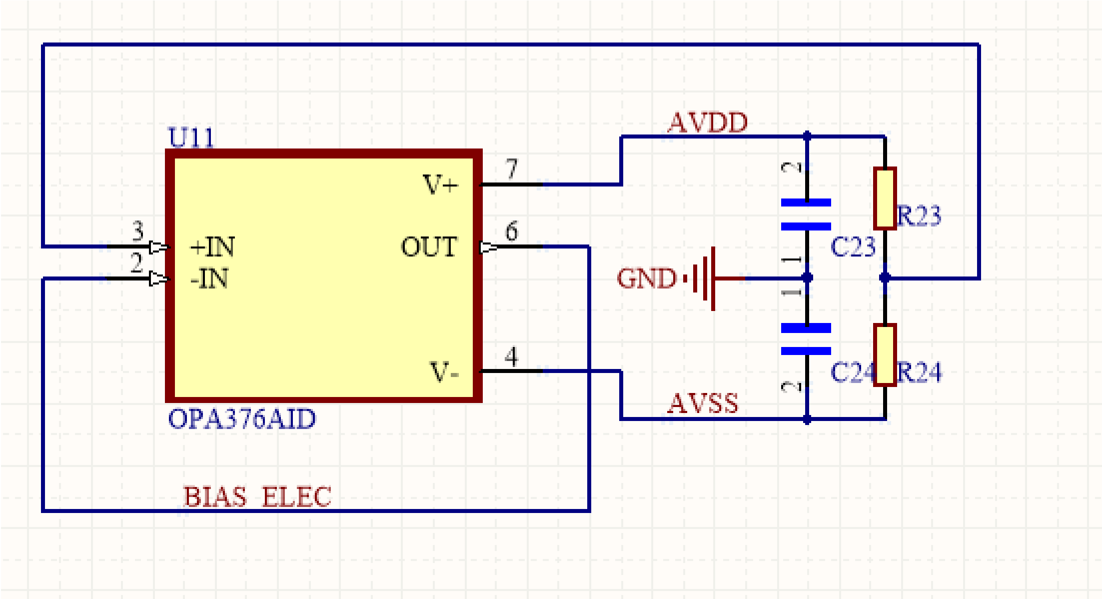

Figure 3.32 Reference Op-amp

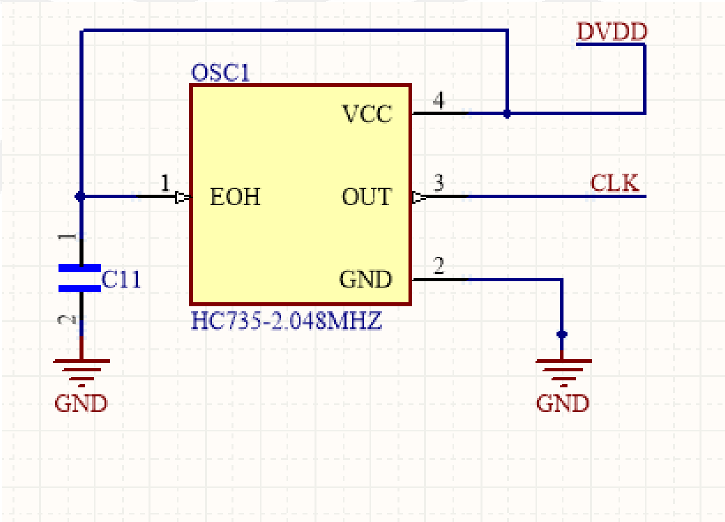

Figure 3.33 External Cyristal Clock

The original electronic board developed was designed using the Altium Designer program. There are 3 main parts in the design: The first is the power layer shown in Figure 3.27- 3.28. In this layer, 5 volts is taken and converted to -2.5V and 2.5 volts, thus obtaining the symmetrical voltage required for ADS1299.The second is the part where ADS1299 and electrodes are connected. As seen in Figure 3.29, the signal is passed through a low pass filter after the connector where the electrodes are connected. The signal passing through the filter enters the ADS1299 as seen in Figure 3.31. In addition, an external crystal oscillator has been added for the ADS1299, as shown in Figure 3.33.Thirdly, ESP32's connections are made for SPI communication with ADS1299, to provide power to it. Connections are shown in Figure 3.30.

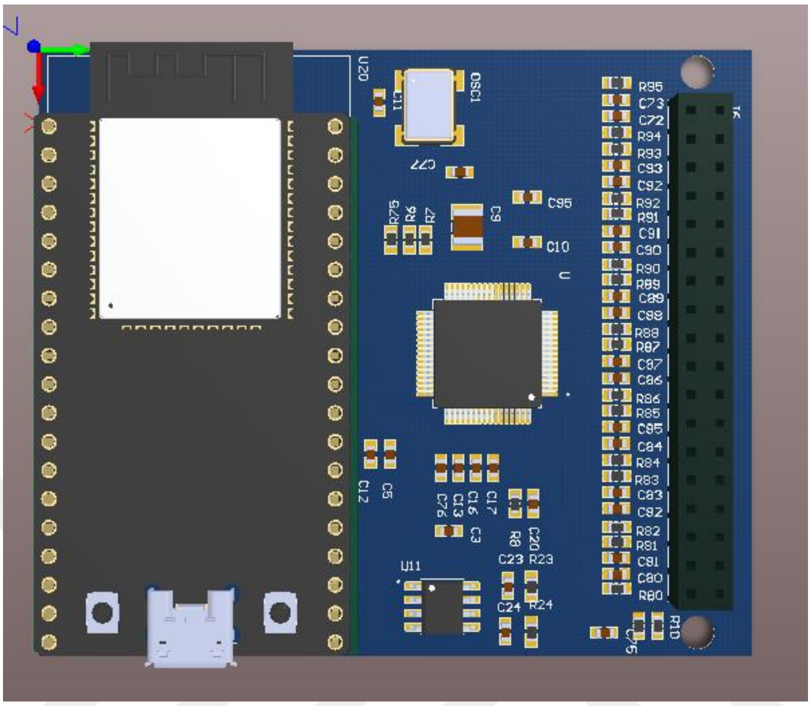

Figure 3.34 PCB board 3D shape from Top

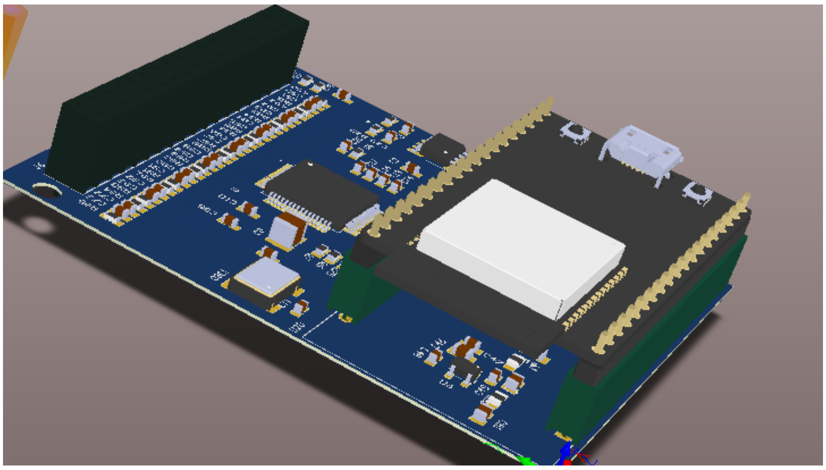

Figure 3.35 PCB board from isometric view

The printed circuit design of the electronically designed and drawn circuit was also done in the same program. The recommendation designs of the component manufacturers were used while placing the components and making the connection paths. The dimensions of the designed circuit are 56x66 mm. 3D view of the circuit is given in Figure 3.34-3.35.

4. RESULTS AND DISCUSSIONS

The aim of this study is to produce an 8-channel, dry electrode, wireless, portable, low-cost and open source EEG signal collection device. As a result of the studies carried out in this direction, the first prototype was produced and an original and lower cost electronic card, which can be seen in Figure 3.35, was designed by making improvements with the information obtained from the produced prototype. The ADS1299 IC used in the prototype ensures that the device has a 24-bit resolution, low noise, has low power consumption and is low in cost. By using ESP32, an external Bluetooth module was not used for wireless communication, and data was transferred quickly with a 32-bit, 2 core, and 240 MHz processor. The prototype works for 24 hours which is a longer time period compared to commercial EEG devices with a total of 6000 mAh 3.7 Li-po battery it has. The comparison of devices can be seen in the Table 2.1-2.2.

ADS1299 is designed for EEG devices and is an integrated circuit used in licensed medical devices. However it is costly and considering alternative ICs decreases the cost of the device. In addition, the ESP32 WROOM development board used in the project, which used in industrial applications, has a very high rate compared to its other counterparts when the performance/price comparison is made. In Table 4.1, the approximate cost of mass production of the prototype is given.

Table 4.1 The cost of the prototype BCI system, based on approximate estimations.

No:	Component	Cost estimate (USD)
1	Headset 3D Printing	10
2	Dry Electrodes	10
3	Electronic PCB board	80
4	ESP32 WROOM32D	8
5	Accessories	5
6	Battery Pack	30
Total Cost estimate		143

The accuracy of the device named AyyıldızBCI in this thesis, collects EEG signals and the factors affecting the received signals were found using various methods: The first of these methods is to enable the automatic test signal generated directly by the ADS1299 integrated circuit. The accuracy and losses of the data flow between the user interface and the device were investigated. As a result, it has been determined that the generated test signal is transmitted from the device to the computer interface for all channels, without any negligible very small losses, and that the interface program processes the incoming data and records it again without error. The second method is to detect noise and disturbances in the data received from the electrodes, and to find any errors that occur when converting from analog to digital. For this purpose, various frequencies and types of voltage were applied between the channel electrodes and the bias electrode by using a signal generator. It has been investigated whether this applied voltage is read by the device and whether it receives noise. As a result of the experiments, it has been observed that the device works flawlessly at voltage values starting from very small amplitudes between DC voltage and 1-120 Hz (since EEG signals are in this range), up to 5V. In the third method, readings were taken by touching the electrodes of the device to the skin surface. When these received data were examined, a DC bias was detected between 10-30mV, caused by the impedance between the skin electrode, as in other devices. By updating the computer interface, this DC bias has been removed from the signal, Therefore EEG signals between 1-100µV can be observed very easily. Fourthly; while receiving EEG signals, blink artefacts, which can be easily seen on the signal, were examined and it was observed that blink artefacts occur in real time in EEG signals when blinking. The effect of blink states on the signal can be seen in the Figure 4.1.

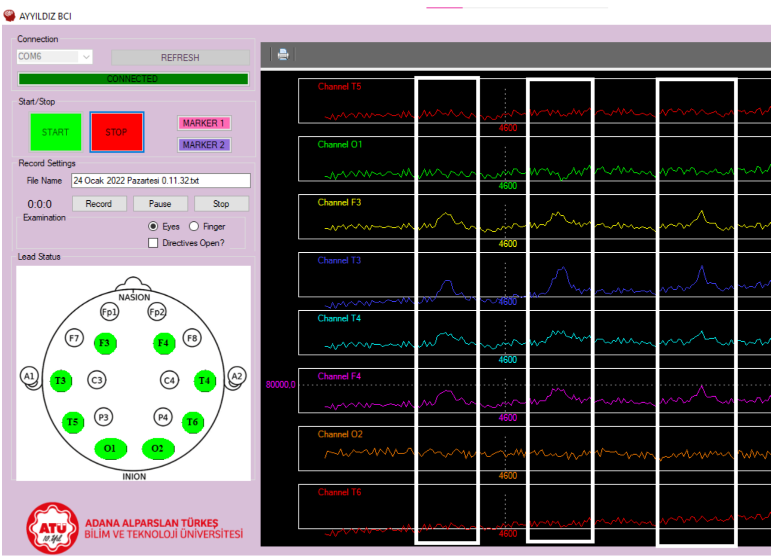

Figure 4.1 Effect of blink states on signal

5. CONCLUSIONS

Remarkable progress has been achieved in science and technology in the last century. Scientists have discovered the unknown and solved many problems. However, what we know about the functions of the human brain is still very limited. EEG is one of the ways of solving the mysteries of the human brain. The clustered signals produced by the brain can be collected by means of EEG and provide important information about the functions of the brain. In this thesis, a portable, wireless and low-cost device has been developed and produced for collecting high-quality EEG signals. In addition, the device will be open source code and will be available for researchers and open to development. As a result, researchers and developers will be able to obtain this device and do more research on EEG, or by making changes in the design and codes of the device, they will be able to produce devices with new and superior features. The first prototype was designed and produced successfully. Some key features of the designed EEG device:

- It has 8 channels and can be up to 32 channels with the daisy chain method.
- Starting from 128 samples per second up to 500 samples
- Using Bluetooth, it establishes a wireless connection with the computer.
- It can be connected to the computer's internal Bluetooth without the need for an external connection module.
- Dry electrode was used. It does not require paste or solution during application.
- The device is modular and there are empty slots on the cap where electrodes can be connected allowing to increase the number of channels if needed.
- Due to the lead off detection, it can be seen from the computer interface whether the electrodes are in full contact or not.
- By reason of its 6000 mAh batteries and low power consumption, it can be recorded for 24 hours.
- The batteries are rechargeable and the device can be charged via USB.
- Thanks to the simple and user-friendly interface, you can easily connect to the device and start using it.
- The received signals can be instantly observed on the graph without any noticeable latency.
- Received data can be saved in .txt, .csv or .edf format.
- The cost was only 143 USD thanks to the newly designed card.

- It receives very low noise because it is wireless and the integrated components used are developed for the EEG device.

Using several different methods, the accuracy of the signals collected by the device was evaluated and it was seen that the developed device collected more noise-free and consistent data than many other devices on the market.

This prototype is developed for an 8 channel application. Even though the device is made suitable for a modular design, if the number of channels needed increases some changes are needed. Because the ESP32 WROOM card used is sufficient for an 8-channel application, the losses increase as the number of channels or the number of samples per second increases. Therefore, alternative processors should be considered for a device with more channels and a higher sampling rate. Another downside of the device is the traces it leaves on skin in long recording experiments due to the dry electrode used in the device. The trace caused by the electrode can be seen in the Figure 5.1.

Figure 5.1 The trace left by the electrode on the skin

6. RECOMMENDATIONS

Here are some of the problems and solutions suggested for the prototype device:

- Due to the shape of the electrodes, it might cause temporary pain on the surface it contacts, this problem can be solved by using different types of electrodes and/or electrodes in different forms.
- Due to the use of dry type electrodes, the impedance between the skin and the electrode is higher than the electrodes using solution. This causes a large DC bias in the received signals. Although this problem can be solved in software. Electrodes with different types of alloys that can lower the impedance can be tried.
- In this study, a large battery pack was used to extend the usage time, but the size of the battery pack used in the Device could be smaller, thus increasing portability and ease of use and reducing cost.
- Real-time FFT graphics can be added on the user interface.
- When the computer's own bluetooth is used, no other device should be connected via bluetooth. Because the density caused by the device sending a large amount of data should not be blocked by other devices.
- Cross-validation can be done by performing the same experiments using a future prototype and other commercially available devices. In this way, the accuracy and consistency of the device compared to other devices can be determined. We plan to perform the necessary experiments for the prototype after obtaining the legal permissions for data collection
- Materials produced using a 3D printer can be produced faster and more robustly using methods such as plastic injection.
- Wearability can be improved by making improvements on the cap design.

7. REFERENCES

Action potential. (2021). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Action_potential&oldid=1060938852

Arduino Buying Guide 2020: Complete Guide to Choose the Right Board. (2020, March 3). *Electropeak*. https://electropeak.com/learn/arduino-buying-guide-how-to-choose-right-arduino-board/

Balim, M. A., & Acir, N. (2018). 8 Channel Mobile EEG Measurement Device Design. *2018 Medical Technologies National Congress (TIPTEKNO)*, 1–4. https://doi.org/10.1109/TIPTEKNO.2018.8596959

Biyomedikal Cihaz Teknolojileri,Elektrotlar. (2011). T.C. MİLLİ EĞİTİM BAKANLIĞI.

Could OpenBCI support Texas Instruments ADS1299EEGFE-PDK ? (n.d.). OpenBCI Forum. Retrieved May 24, 2021, from https://openbci.com/forum/index.php?p=/discussion/2686/could-openbci-support-texas-instruments-ads1299eegfe-pdk

Dry EEG Comb Electrodes (Pack of 30). (n.d.). OpenBCI Online Store. Retrieved January 26, 2022, from https://shop.openbci.com/products/5-mm-spike-electrode-pack-of-30

EEG-Headset comparison table. (n.d.). EEG-Headset Comparison Table. Retrieved July 2, 2021, from https://www.mindtecstore.com/EEG-Headset-comparison-table

Eraldemir, S. G., Arslan, M. T., Yildirim, E., & Koç, F. (2019). THE EFFECT OF THE ENVIRONMENT ON BRAIN ACTIVITY DURING PROBLEM SOLVING. *The Journal of Cognitive Systems*, *4*(2), 34–37.

Eraldemir, S. G., Kiliç, Ü., Keleş, M. K., Demirkol, M. E., Yildirim, E., & Tamam, L. (2020). Classification of EEG Signals in Depressed Patients. *Balkan Journal of Electrical and Computer Engineering*, *8*(1), 103–107. https://doi.org/10.17694/bajece.631951

ESP32WROOM32D & ESP32WROOM32U Datasheet. (2021). Espressif Systems. https://www.espressif.com/en/support/download/documents.

Feuer, A. (2021). *Adamfeuer/ADS129x-tools* [C++]. https://github.com/adamfeuer/ADS129x-tools (Original work published 2013)

Hendarwin, H., Wijaya, S. K., Prajitno, P., Ibrahim, N., Gani, H. S., & Apriadi, W. (2019). *EEG data acquisition system 32 channels based on Raspberry Pi with relative power ratio and brain symmetry index features*. 050003. https://doi.org/10.1063/1.5139376

International 10-20 System. (2021). Evoked Potential. https://www.evokedpotential.com/international-10-20-system.html

Memon, S. A., & Waheed, A. (2018). *Beyin-Bilgisayar Arayüzü Uygulamaları için Düşük Maliyetli Taşınabilir 4 Kanallı Kablosuz EEG Veri Toplama Sistemi Low-Cost Portable 4-Channel Wireless EEG Data Acquisition System for BCI Applications*. 4.

Nacy, S., & Kbah, S. (2016). *Brain Computer Interface, EEG signal, Motor cortex*. 9.

Özdamar, E. Ö. (2009). *EEG ANALİZİNDE BAĞIMSIZ BİLEŞENLER*. Mimar Sinan Güzel Sanatlar Üniversitesi.

Penney, D. G. (2022, January 23). *Brain parts*. http://www.coheadquarters.com/coOuterBrain1x.jpg

Rashid, U., Niazi, I. K., Signal, N., & Taylor, D. (2018). An EEG Experimental Study Evaluating the Performance of Texas Instruments ADS1299. *Sensors*, *18*(11), 3721. https://doi.org/10.3390/s18113721

Sahin, M. E., Bascil, M. S., & Temurtas, F. (2015). *Design of Prototype EEG Signal Card*. *1*, 9.

Stangor, C., & Walinga, J. (2014). *Introduction to Psychology—1st Canadian Edition*. BCcampus. https://opentextbc.ca/introductiontopsychology/

Texas Instruments Incorporated. (2012). *Texas Instruments ADS1299IPAG datasheet*. Texas Instruments Incorporated. www.ti.com

APPENDICES

All the codes, circuit diagrams and 3D designs created within the scope of the thesis can be found on the Github repository: Https://github.com/Himmetayyildiz/AYYILDIZ_BCI