

Toward Wearable Multimodal Neuroimaging

An Interactive Qualifying Project
submitted to the faculty of

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by

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Introduction

1. Introduction of BCI and EEG Device

The human's brain is the most complex part of the human body as it controls every aspect of human life. This complex organ consists of multiple parts, the main ones being the cerebellum, brain stem, and cerebrum. Each brain hemisphere (parts of the cerebrum) has four sections, called lobes: frontal, parietal, temporal and occipital. Each lobe controls specific functions. (Farnsworth, 2020) The brain is composed of billions of cells, half of which are neurons, and half of which help and promote the activities of neurons.

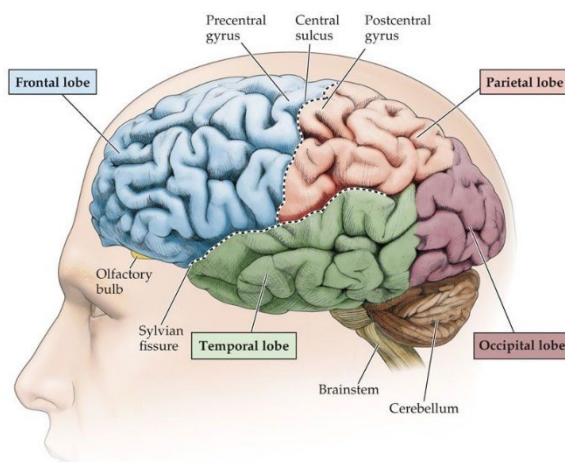


Figure 1: Four cortexes of the brain

In these areas, neural activity and synapses make connections between neurons. Any synaptic activity produces a subtle electrical pulse called postsynaptic potential. When thousands of neurons discharge synchronously, they generate an electric field strong enough to spread to tissues, bones and skulls. Finally, it can be measured on the head surface.

BCI (brain-computer interface) is a technology for sending and receiving signals between the brain and external devices. It collects and interprets brain signals, then transmits them to an external device that outputs instructions related to receiving brain signals. The simplified BCI definition describes the technology as "a direct communication link between the brain and external devices." This connection is a two-way link (two-way interface). One direction involves the BCI sending brain activity to a computer, which then translates the brain activity into motor commands. Communication can also happen in the other direction - the computer sends

information directly to the brain of the BCI user. In contrast to non-invasive passive BCI, which is called active BCI, there is a direct brain connection.

BCI is divided into three types: non aggressive, semi aggressive and aggressive. In invasive techniques, special devices must be used to acquire brain signals, which are directly inserted into the human brain through surgery. In the semi-invasive type, the device is inserted into the skull at the top of the human brain (NEUROTECHEDU, 2018). In general, non-invasive is considered the safest and lowest cost equipment type. However, due to the blockage of the skull, these devices can only capture "weak" human brain signals. Brain signals are detected by electrodes placed on the scalp. (Gonfalonieri, 2018)

The availability and reliability of EEG signals make it the most commonly used method for brain-computer interfaces. Many EEG-based BCI devices have been developed using traditional wet or microelectromechanical systems (MEMS)-type EEG sensors. However, at present, for most EEG devices, the electrodes are installed in elastic caps similar to bath caps to ensure that data can be collected from the same scalp position of all respondents. EEG equipment will be bulky and complex in design, which cannot meet portability. Therefore, obtaining EEG signals comfortably and conveniently is an essential part of a new BCI device.

In our project, our EEG equipment is used to detect and improve sleep. In the current market, the signal acquisition of EEG equipment is generally composed of multiple electrodes, which is bulky and complex in design and cannot meet the portability. Therefore, our goal is to design the EEG device into a cuboid shaped devices with a side length of 3cm and a height of about 1cm. It can be hung on the ear like a sports headset. Meanwhile, the maximum tolerance time of our EEG equipment was 10 hours. Although the service life of our equipment is shorter than that of

some products with a service life of more than 20 hours, our equipment is sufficient to be used at this capacity.

2. Applications of BCI and EEG Device

BCI establishes a new communication between the brain and the external environment that does not depend on peripheral nerves. The BCI and EEG device plays a vital key technology to promote social development in the future. Because of the market potential, many companies and research institutions are deeply engaged in this field. As a result, understanding the applications of this technology will provide us with a comprehensive view of the market.

Following paragraphs briefly introduces the current application of the BCI devices with an EEG system, including medical uses, helping long-term laborers be more focused, educational uses, and virtual entertainment enhancement.

2.1. Helping paralyzed regain the ability of speaking

The output of a brain-computer interface system may replace natural outcomes lost due to injury or disease, such as text output by a person who has lost the ability to speak through a brain-computer interface or speech through a speech synthesizer. Patients with severe movement disorders, such as the late famous physicist Stephen Hawking, myasthenia gravis patients, and patients with high paraplegia due to accidents, are important application objects of such brain-computer interface systems. The common feature of these patients is that they have relatively intact thinking ability but have lost voluntary control of muscles and the peripheral nervous system, so they cannot effectively express their needs and ideas to the outside world. This patient group's most essential need is to convey the information in their minds through auxiliary means.

2.2. Restoration of lost cognition

The output of the brain-computer interface can restore lost function. For example, cochlear implants have helped hundreds of thousands of deaf patients restore hearing; artificial eyeballs can help blind patients see things again, and so on. In addition, after a stroke, patients lose the ability to control their limbs; they can also use brain-computer interface technology to train the patient's cerebral motor cortex to help the patient recover.

2.3. Long-term worker and student cognitive enhancement

In engineering psychology, the cognitive load and fatigue level of motor vehicle drivers, pilots, air traffic controllers, and other unique job positions are significant for job performance and safety. The real-time monitoring data provided by the brain-computer interface offers a crucial objective basis for work management, which can better ensure personnel safety and work performance. Australia's SmartCap has commercialized the application. The user's fatigue status can be monitored in real-time by implanting electrodes in baseball caps. In education, the brain-computer interface can conduct a real-time evaluation of students' attention levels and provide a reference for teachers' teaching arrangements. In marketing, brain-computer interface technology can be used to evaluate the emotional experience of viewers watching advertisements, movies, TV, and other media content and the user experience in a more generalized human-computer interaction scenario. (Ker, 2015)

2.4. Virtual entertainment mechanism supplement

For the control field, in addition to the manual control method, a brain control method can also be added to realize multi-modal control. Here, the brain-computer interface is a supplement to the original single control method. In in-game entertainment, the brain-

computer interface provides game players with a new operational dimension independent of traditional game control methods, enriching the game's connotation and improving the game experience. (Cattan, 2021)

2.5. Patients' rehabilitation improvement

For example, in rehabilitation, for stroke patients with damaged parts of the sensorimotor cortex, the brain-computer interface can collect signals from the damaged cortex and then stimulate muscles or control orthoses to improve arm movement (Cervera, 2018). The brain of epilepsy patients will have an abnormal discharge of neurons in a particular area. After the abnormal release of neurons is detected through brain-computer interface technology, corresponding electrical stimulation can be performed on the brain to reduce epileptic seizures (RN, 2018). The motor imagery brain-computer interface plays an essential role in the rehabilitation training for children with autism. Compared with normal children, children with autism have weak imitation motivation when watching other people's sports situations, and the corresponding activation of the sensorimotor cortex is lower (Xu, Song, Ren, Wang, & Zhao, 2013). When these children participate in game projects, real-time feedback of their sensorimotor cortex activation can improve their self-control of sensorimotor cortex activation, thereby improving autism symptoms. Similar neurofeedback training paradigms for brain-computer interfaces are also expected to treat ADHD, depression, etc., positively.

3. Unexplored Market Study and Business Ecosystem

Considered strategic for several reasons, BCI stands for a potential next-generation hardware interface that is on the verge of a significant change in how user control devices. In the next few years, controlling devices with the human brain will become the norm.

In addition to those markets where BCI devices are already widely used, such as medical perspective, virtual entertainment, and health supplies, we found advertisements, mass media, and even the financial field have great potential for application.

The marketing/advertising field can generate huge profits. While there are currently no devices (corrections welcome) or apps designed for marketing, research suggests that BCI will be used in these areas in the future (Johnson & Vitka, 2013).

Several studies have indicated that BCI can measure the attention generated by commercials. As a result, many companies would be interested in developing a solution to measure critical KPIs for marketers (Sanu Thomas, 2022).

The market for commercial non-intrusive BCI is still in its infancy, and companies are still trying to figure out the best way to do it. We believe that BCI will take another two or three years to enter the mainstream. Some industry experts estimate that the main challenge is to "find a middle market that could benefit from early iterations of BCI."

Creating BCIs that are easy to use, accessible, intuitive, secure, and highly accurate remains a significant challenge. Here we listed multiple aspects of those challenges, usable equipment can acquire reasonable data, practicality, ecosystem build up, and commercial market supervision.

- **Equipment**

The equipment is a big challenge (expensive, difficult to operate). Some companies are working on developing sensors integrated with earbuds to monitor brain activity. Plus, everyone's data needs to be highly calibrated, and we're far from smart devices like smartphones.

- **Proven Usefulness**

It was difficult to convince consumers to buy BCI. Do people want to wear one device on their heads to control another? A remote controller is sufficient to turn on the lights. We expect more startups to try to find the best apps. It is a significant risk for BCI startups due to substantial technological development and investment. It is also difficult for us to set a suitable price for BCI applications (Kögel, Jox, & Friedrich, 2020). Finding the right balance between production costs and retail prices was no easy task for BCI.

- **Pilot Project**

Several BCI companies have considered pilot projects (from BCI to wearables). Some commercial applications, such as sleep, monitoring already represent a crowded market. In the short term, finding relevant and unique intermediary applications for BCI users is critical.

- **Brain Waves (EEG)**

Another potential problem with BCI applications worth mentioning is related to EEG data. For non-invasive BCI, the tissue between the skull and the electrodes and brain causes weaker signals and slower transmission of information, preventing the user from controlling the device (Simanto, A., & Ahmed Khawza, 2021). Researchers are working to overcome these barriers and enhance the utility of EEG for medical and non-medical applications. In addition, in some cases, the user has to go into a meditative state to control brain activity, which controls the device. Finally, current non-invasive BCIs require a lot of intensive training.

- **BCI Application and Market Ecosystem**

One of the main challenges facing BCI companies is integrating an ecosystem of solutions from other companies. In the future big tech companies decide to build BCIs that

only apply to specific products, it will be difficult for startups to compete with them. So, ultimately, BCI enhances the lock-in effect.

BCI plays an essential role in the smart home industry and may also replace smartphones in the long run. However, the non-intrusive BCI industry will resemble the smartphone industry (monopoly by a few).

The application of BCI in the field of intelligent environment is not limited to the home, there are also BCI designed for the workplace or the automotive industry, but there are only a few BCI devices and various "applications" made by many other companies on the market today (Gonfalonieri, 2020).

- **Market supervision**

The industry is plagued by not knowing which devices are compliant with BCI (consumer side). Also, questions about brain data remain vague. Can the EEG company sell brain data? Do they have to comply with specific regulations, such as the General Data Protection Regulation (GDPR)? What to do if BCI is hacked?

For medical devices, "the U.S. Food and Drug Administration (FDA) regulates everything - including certain BCIs. However, some BCIs are not classified as medical devices and are sold directly to the consumer market" (Health, 2021)

4. List of Potential Commercial Non-invasive and Nonmedical BCI

Applications

Here we provide list of potential commercial applications of BCI devices.

- Sleep pattern analysis (Kesper, 2011)

- Workplace Analysis/Maximizing Productivity: For example, some projects are developing programs to analyze operator cognitive status, mental fatigue, and stress levels. (Maher Chaouachi, 2011)
- Mood detection: For example, a system that monitors the user's brain, constantly adjusting to the environment based on temperature, humidity, light, etc. Recently, Nissan partnered with Bitbrain to launch the prototype of a brain-car interface (Okuda, 2018).
- Emotion analysis (M.Joshi & B.Ghongade, 2022)
- Equipment control (e.g., robotic arms)
- Personal identification system using brain waves: Facilitate body movement and reduce reaction time with transcranial direct current stimulation (J, et al., 2017)
- Workplace Analysis/Maximizing Productivity: For example, some projects are developing programs to analyze operator cognitive status, mental fatigue, and stress levels.
- Marketing: In marketing, EEG can be used to assess the level of attention generated by commercial and political advertisements in different media (A, S, L, U, & G, 2020). BCI also gives ad memory insight. Overall, BCI can be used to optimize online advertising or TV advertising.
- Education: In education, BCI can help verify whether each student is clear about what they have learned, allowing teachers to customize their interaction with each student according to the learning effect (Cai, Liu, & Liu, 2022).
- Entertainment: In entertainment, BCI can be used for video games. For example, a player can control a character with just one BCI. In addition, when watching a movie, BCI can help create an interactive movie viewing experience through the viewer's brain activity. In the

future, audiences can gain an immersive adventure through the full range of brain activity to control the movie together. (Abu-Rmileh, 2019)

- Military: In the military field, "BCI has been used by the military for the U.S. Defense Advanced Research Projects Agency (DARPA) drone test."

Product Development

Most EEG devices we found on the market are those bulky devices that requires several professional staff to set up and manipulate (**LaFountain, Marshall, Pacheco, & Rogers, 2022**) (**Lam, Sullivan, Richards, & Stevens, 2021**). Normally the operation of the EEG device includes many redundant processes, like placing many electrodes around tester's head, which requires staff to have professional training experience. Not to mention that the data recorded needs to be assessed by experienced neuroscientists. Our envision for this project is to build an EEG portable device for public to use with easy set up and guiding. We wanted to build a single channel EEG device that can record neural activity in real time and transfer the data package to a smart phone through Bluetooth connections. We think a reasonable size for this EEG device should be no larger than a hearing-aid. The wearing process should be easy and intuitive, similar to putting on the headphone. The bundled app that we plan to develop will provide wearing instructions and basic analysis to user's neuroactivity data. As we focus on the neuroactivity during sleep time for this stage, we also require the device to run for at least 12 hours on a single charge of the battery. We divided the product development into three parts, including the hardware, software, and the enclosure design. The product development objectives are listed as below:

- Single channel EEG device

- Detachable design from enclosure
- Portable size
- 12+ hours battery life
- Bluetooth connection with smart phone
- EEG data processing
- App with wearing instructions and analysis to user's neuroactivity data

5. Hardware Development

To record the electrical activity generated by the brain, electrodes need to be placed on the scalp surface of the user's head. The patterns and frequencies of these electrical signals can be measured on the scalp. With various requirements, including size, power consumption, and channel, we found the TGAM from NeuroSky perfectly fits our needs, which is a module that can receive and process all the data from electrodes. With electrodes connected to the TGAM, we can measure analog electrical signals, commonly referred to as brainwaves, and processes them into digital signals. These measurements can be later transferred out wirelessly through the Bluetooth module for further processing and analysis. As a portable device, it also needs to have a battery and charging design. In order to take full control of the TGAM and achieve customized functionalities as our expectation for developing a product, we need to redesign the TGAM to make the overall system

more compact and complete. The redesigned TGAM and Bluetooth

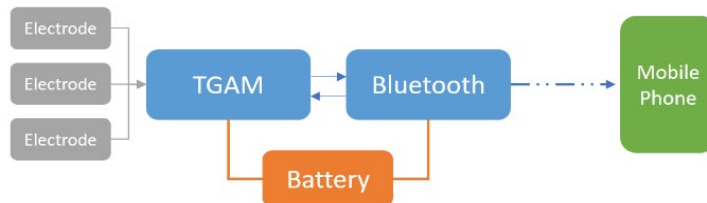


Figure 2: System Architecture Overview

module will be soldered together as one piece and mounted in the enclosure with the battery.

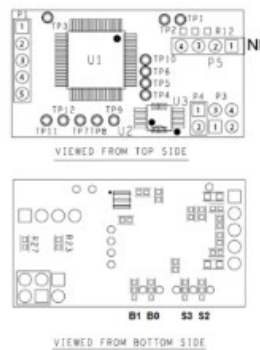
5.1. System Architecture Overview

5.1.1. TGAM

TGAM is the product from NeuroSky that enables a device to interface with the wearer's brainwaves. It includes the sensor that touches the forehead, the contact and reference points on the ear pad, and the onboard chip that processes all the data and provides it to software and applications in digital form. Both raw brainwaves and the eSense Meters (Attention and Meditation) are calculated on the ThinkGear chip.



Figure 3: Top view picture of TGAM



- Header P1 (Electrode)
 - Pin1: EEG Electrode "EEG"
 - Pin2: EEG Shield
 - Pin3: Ground Electrode
 - Pin4: Reference Shield
 - Pin5: Reference Electrode "REF"
- Header P3 (UART/Serial)
 - Pin1: GND "-"
 - Pin2: VCC "+"
 - Pin3: RXD "R"
 - Pin4: TXD "T"
- Header P4 (Power)
 - Pin1: VCC "+"
 - Pin2: GND "-"
- Header P5 (Notch Filter Configuration)
 - Pin1: VCC "+"
 - Pin2: NF Pad
 - Pin3: GND "-"
 - Pin4: TGAT OSC_IN

Figure 4: TGAM Top view and bottom view

5.1.2. TGAT

TGAT is a low power chip on the TGAM that can record and transmit EEG data. The range of operating voltage of TGAT is from 2.97VDC to 3.63VDC, under 15mA current.

(NeuroSky, TGAT Datasheet, 2016)

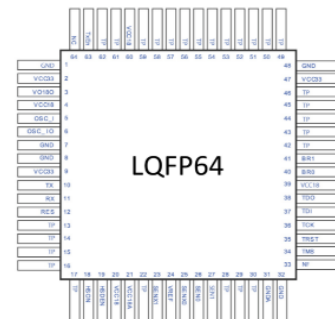


Figure 5: Baud rate chart and TGAT top view (detailed schematic of the LQFP64 can be found in TGAT datasheet)

5.1.3. Bluetooth Module

EEG device requires a Bluetooth module for receiving data packages from TGAM and sending data to portable devices, PC or smartphone. The Bluetooth module we use is the RN4870. The RN4870 Bluetooth Low Energy module is designed for easy implementation into a broad range of applications. It delivers up to 2.5x throughput improvement and more secure connections vs. Bluetooth 4.1 based products. Developers can easily work with the device via a standard UART interface, available on most Microcontrollers and Processors.

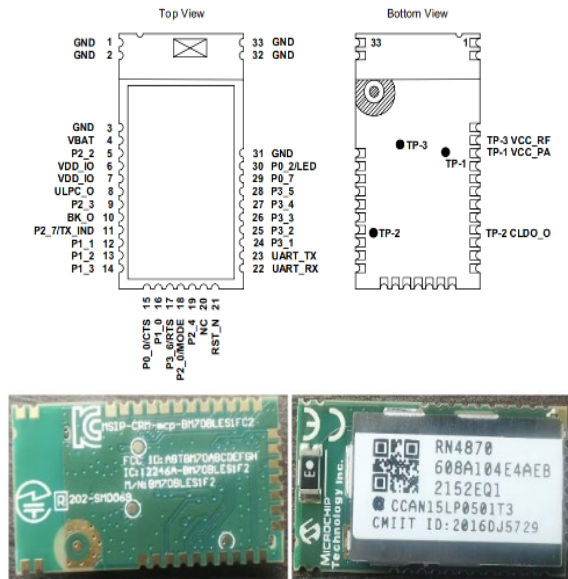


Figure 6: RN4870 top view and bottom view

5.1.4. Electrodes

An electroencephalogram (EEG) is a test that measures electrical activity in the brain using small, metal discs (electrodes) attached to the scalp. Brain cells communicate via electrical impulses and are active all the time, even during asleep. This activity shows up as wavy lines on an EEG recording. (Staff, 2022)

5.2. Schematic

For starting to build a PCB, a completed schematic is necessary. It is important because the components layout and the trace are based on the schematic we designed. A good schematic should imply the following features:

- Block Diagram
- Power Supply
- MCU interface
- Memory interface
- Revision history

In our design, we benefited from the information provided by the manufacturers and previous design.

5.2.1. Preparation

Before drawing the schematic, we need to get the information of the components we need. Each PCB design app has a corresponding file type, and we can get those files easily from components selling companies like Mouser and Digikey. These files contain symbols and footprints of the electronic parts. Symbols are used in drawing the schematics and footprints are used in PCB layout.

5.2.2. Device Hierarchy

The basic connection of two devices is using UART communication. Here is the schematic below:

We added two 0 Ohm resistors, which are usually used as a jumper or cross-track links in normal circuit design, in between two devices for individual use of the RN4870, with the resistors on, two devices are connected and without them, the Bluetooth will connect its UART to our extension jumper. The reason for designing this connection is that we need to configure the Bluetooth sometimes. To configure RN4870, we also need to set the pin 18 mode pin to high, so we put another 0-ohm resistor there for configuration.

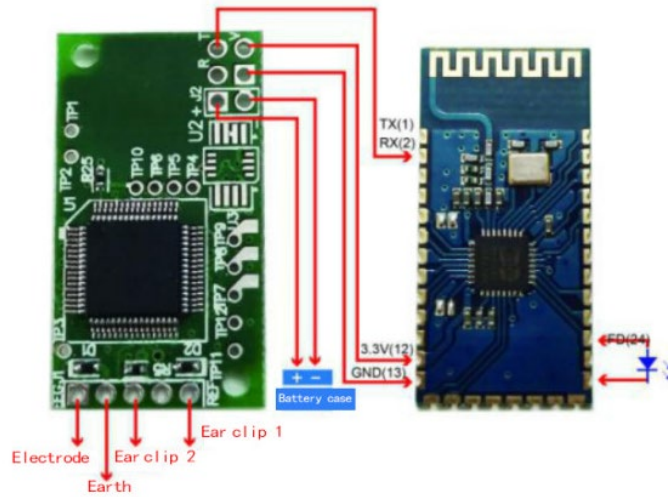


Figure 7: Product device sample hierarchy

5.2.3. Power Distribution

One new feature we added to our product based on the TGAM chip is the 3.3V linear regulator. For our need, we need to select a regulator that should minimize the voltage drop and drift with a suitable current that supports all components working in a relatively good condition.

We also added two polarized capacitors with a total of 10 uF of decoupling and the bypass capacitor right next to Bluetooth. Since the TGAM and the Bluetooth are two completely separate devices that shared the same power supply, the function of the bypass capacitors here is to cancel the power supply noise drawing back to the circuit, and with the bypass capacitors, we are able to filter the interference current drawn from the power supply to the ground. For decoupling capacitors, they are designed to neutralize the voltage drop of instantaneous power.

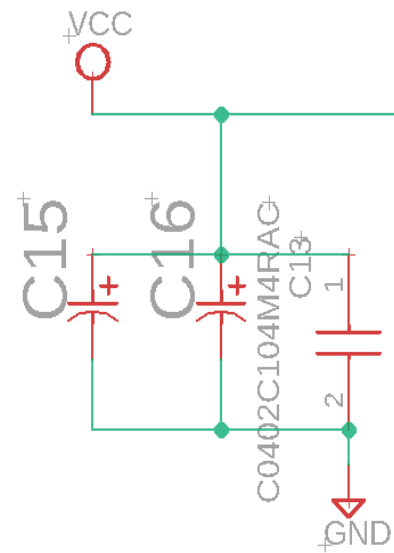


Figure 8: Polarized capacitors for decoupling

5.2.4. Raw data Receiving

To receive the raw data from the EEG device, we should focus on keeping the baud rate of the device at 57.6kHz. There are 4 pull-up or down resistors here for selection. Pin 16 and 17 are defaulted set as connected to the ground. According to the NeuroSky user guide, BR1 to VCC and BR0 to GND is the setting of 57.6k baud rate.

5.2.5. Data Capture

For capturing data, we provide 3 pins and as 1 channel of the EEG device. We need one for electrode, one for ground and another one for reference. This part is the most essential part of the device, we need to handle the signal captured from the electrode and make sure that they are clean and neat. This is where we mainly separate the digital and analog signals.

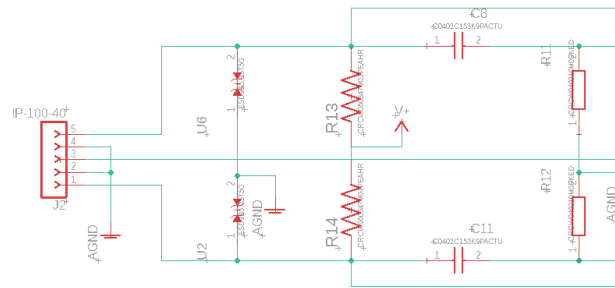


Figure 9: Noise cancellation of raw brain wave signal schematic

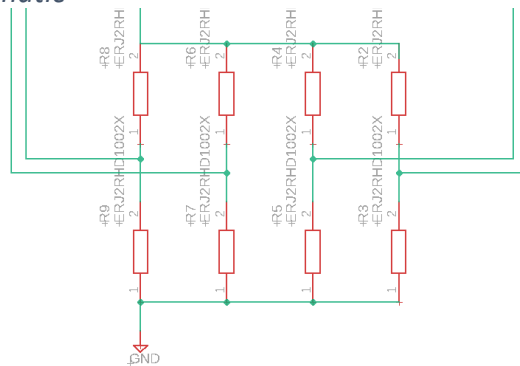


Figure 10: Pull up/down resistors for baud rate configuration and brain wave detection

5.3. Layout

5.3.1. Layout Version 1

The pictures shown below are the scratch layout of the first version of our NEUIRA PCB. The general design idea was to take the original TGAM board from NeuroSky as a reference, keeping the size of the entire PCB close to the original one. In order to achieve this, the most intuitive idea is the double side structure, attaching the Bluetooth module and the TGAM chip on each side of the board, with all the rest capacitors and resistors arranging around the empty area. After the random arrangement of parts on the board and using auto router, we realized that this double side structure makes the NEUIRA PCB too thick for the overall product design. Moreover, all the components on the board are too close to each other, making it extremely hard for routing air wires. Because the size of the smallest battery that we can find for this product is almost twice the size of the TGAM board, it actually allows more room for the PCB. Eventually, we decided to give up the double side structure and work on a new layout of the PCB.



Figure 11: Size comparison of TGAM and battery

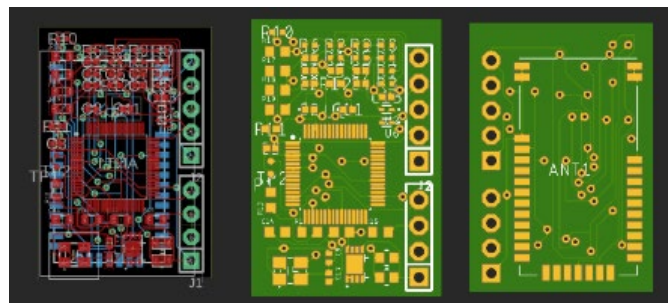


Figure 12: PCB layout of the first version

5.3.2. Layout Version 2

With more space allowed for the PCB, arranging both the Bluetooth module and the TGAM chip on the same side becomes a more reasonable design, which can effectively reduce the thickness of the TGAM board and allow more freedom for the wire arrangement. Based on the size of the battery, we finalized the dimension of the enclosure within 30mm * 30mm.

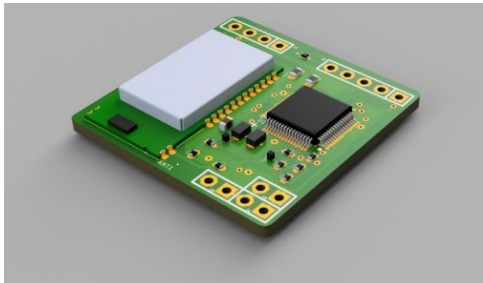


Figure 13: 3D module of the NEUIRA

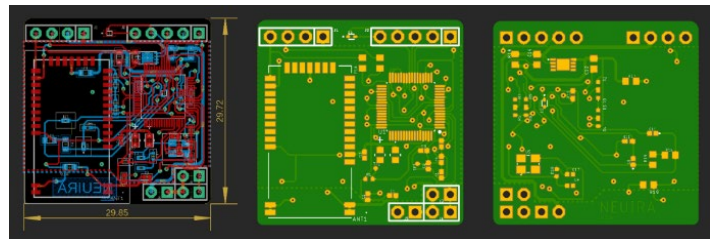


Figure 14: PCB layout of the NEUIRA

5.3.3. Design Details

Several design points were taken into consideration when arranging the component:

- The antenna side of the RN4870 should be aiming towards the edge of the board and the opposite direction of the pinheads for connecting electrodes to avoid noise and interference.
- Bypass capacitors should be placed close to the VCC on TGAM chip and RN4870 to reduce the impact of the current spikes during the switching. It also provides a low impedance path to ground for AC noise signals. (Andy, 2015)
- For configuration resistors that are been used for configuring the frequency, the footprints of those resistors are partially overlapped following the schematic so that they can be pulled up or low simply by switch the position of the resistor.
- There are three sets of female pins on the board, one for the battery, one for the switch, and one for the charging pin. They are placed at the corner for better placement of the switch and the charging pin.

- AGND and GND are connected to the same plane through a 0hm resistor. Although AGND is the return-current path for the analog supplies and GND is the return-current path for the digital supplies, the AGND and GND pins of a device is not isolated internally. Both signals are connected electrically to the substrate of the device and must be connected to the PCB as well. In Eagle, AGND and GND are recognized as two distinct wires that couldn't be connected to each other. A 0hm resistor can be used as a bridge to connect two planes as a whole. (Cadence, 2019)
- RN4870 will be soldered on the board first and then be configured through the RX, TX, VCC and GND pins at the left upper corner of the NEUIRA board.
- Other important design details include:
 - The wire for the VCC should be a lot wider than the normal ones. The width of the wire we use for VCC is 20 mils.
 - The wire that goes in and out from each footprint and via should always be either horizontal or vertical for better connection.
 - The PCB are designed to be rounded rectangle so that it can fit better inside the enclosure.

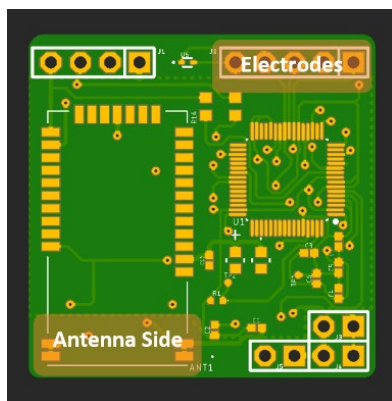


Figure 15: Placement of antenna and the pinheads for electrodes

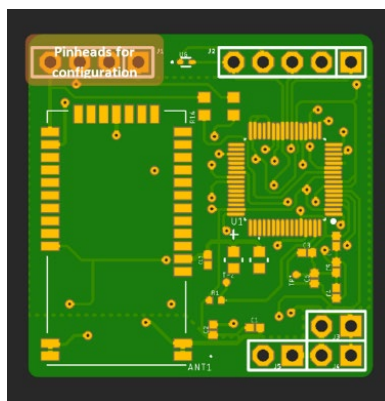


Figure 16: Placement of pinheads for configuring Bluetooth

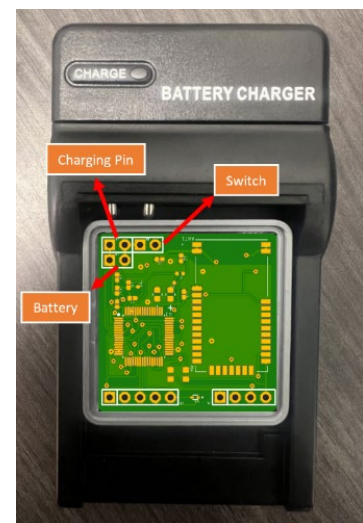


Figure 17: Charging design

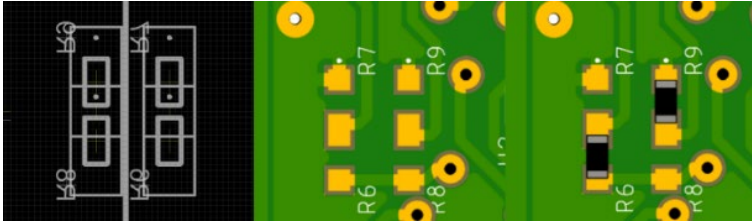


Figure 18: Design of the configuration resistors

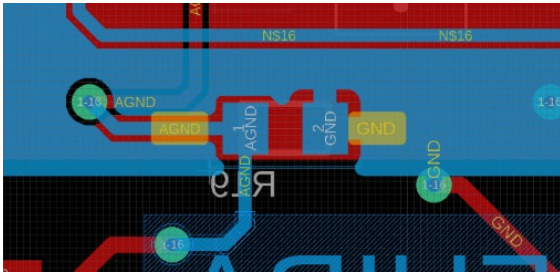


Figure 19: Resistor for connecting AGND and GND

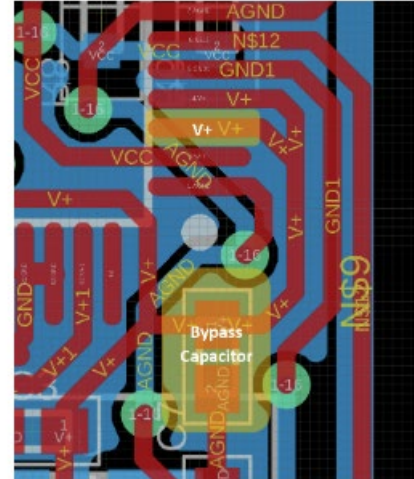


Figure 20: Layout of the bypass capacitors

5.4. Manufacturer

To produce our own PCB, we need to have every detail of the PCB design ready, such as schematic, PCB layout file, bill of material and drill size. All information can be checked using the DCR function in Eagle and check if the PCB meets all the function it has. Contacting a manufacturer is easy, Google the company and click on get a quote. There are a couple of things we need to fill: the size of the PCB, layers, thickness, drill size, minimum track, etc.

We compared a lot manufacturers among nationwide and international, and we found that nationwide companies offer extremely high price if a small amount is needed. We decided to go to a company from Shenzhen, China to help us produce it and they even provide the assembly service. We got the plain PCB boards within 5 days, but the assembly one took a longer time since the components are sometimes out of stock. They provide fast replies and professional suggestions on PCB design for their customers.

6. Software

For the software part of this IQP project, firstly the TGAM chip and RN4870 BLE module were configured and transferred raw EEG data from TGAM to the terminal. Because of the raw EEG data is only data packets, we developed a real-time parsing program. Our program can decode raw EEG data packets to readable data, which can be saved in CSV files. After having those raw data CSV files, we can use MATLAB or other data processing software to plot recorded EEG data. The final step is wireless data transferring, writing the configuration script for RN4870, and receiving desired data package.



Figure 21: USB to serial adaptor

6.1. TGAM Data Read and Transfer

The TGAM chip is a complete EEG single-chip solution provided by NeuroSky. The chip is a highly integrated single-chip EEG sensor, allowing developers to launch their EEG products in the shortest time.

6.1.1. Configuration Procedures

The TGAM chip default setting is 57600 baud rates, we only need to connect the TX/RX pin and we can read raw data from terminal software (Realterm & Coolterm).

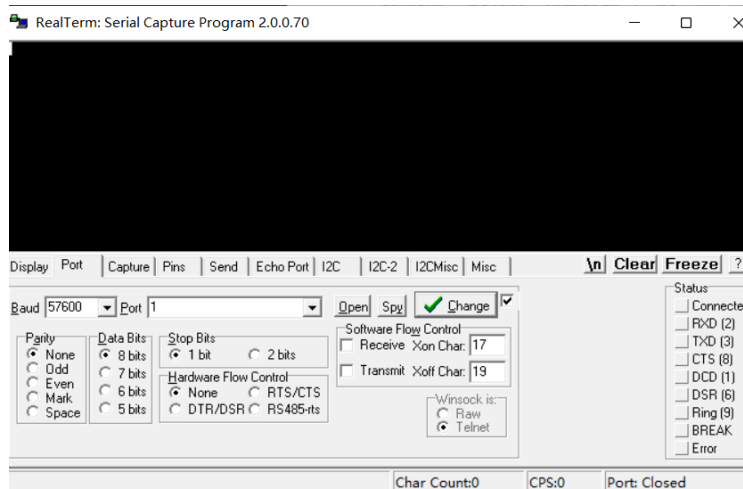


Figure 22: Realterm interface

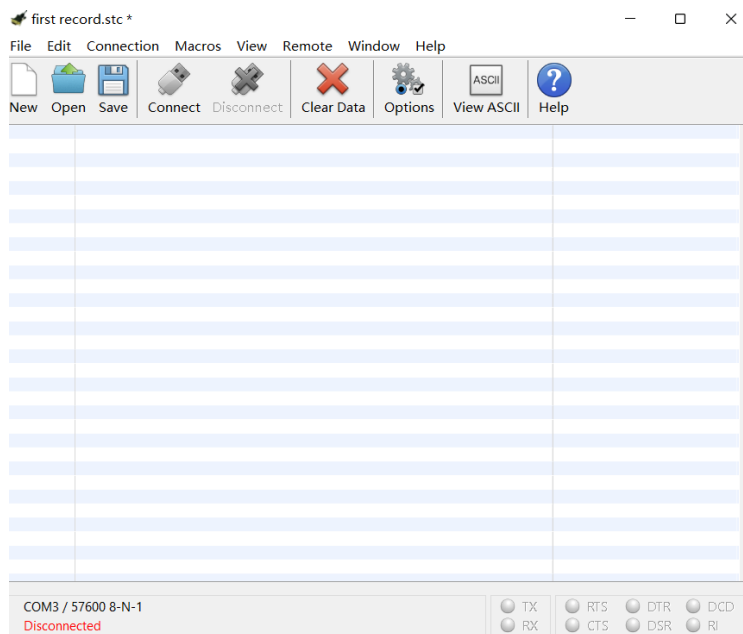


Figure 23: Coolterm interface

6.2. Bluetooth Low Energy Module

6.2.1. Introduction and Background information

Bluetooth Low Energy Module (BLE) is a module that supports Bluetooth protocol 4.0 or higher. It is a personal area network technology designed and sold by the Bluetooth Special Interest Group. It is intended for use in healthcare, sports and fitness, beacons, security, and

Emerging applications in home entertainment. Compared with classic Bluetooth, Bluetooth low energy is designed to support the same communication range while significantly reducing power consumption and cost, allowing wearable devices with higher power consumption requirements to remain powered for a long time. Bluetooth Low Energy uses the same 2.4GHz radio frequency as Classic Bluetooth so that dual-mode devices can share the same antenna. In addition, the modulation system operated by Bluetooth Low Energy is more straightforward.

It should be noted that Bluetooth Low Energy is not backward compatible with the original Bluetooth protocol (that is, classic Bluetooth). Worth mentioning: Bluetooth Low Energy uses the same Adaptive Frequency Hopping (AFH) technology as traditional Bluetooth technology, thus ensuring that Bluetooth Low Energy is stable in "noisy" RF environments in residential, industrial, and medical applications transmission. To minimize the cost and power consumption of using AFH, Bluetooth Low Energy technology has reduced the number of channels from the 79 1MHz channels of traditional Bluetooth technology to 40 channels of 2MHz bandwidth. In addition, compared to traditional Bluetooth technology, a new feature added by Bluetooth low energy technology is the "broadcast" function, through which the slave device can send data to the master device.

Bluetooth Low Energy Principles and Technology. First, its broadcast frequency band and radio frequency turn-on time during broadcasting are reduced: traditional Bluetooth uses 16 to 32 frequency bands for broadcast, while BLE only uses three broadcast frequency bands; the RF turn-on time for each broadcast is reduced from 22ms of traditional Bluetooth to 0.6~1.2ms. Second, it only transfers a small amount of data at a time. Third, its transmission rate is relatively low. Combining the above three characteristics determines that low-power Bluetooth has lower

power consumption and more energy saving than traditional Bluetooth. For example, video streaming, high-quality audio streaming, or transferring large amounts of data are unsuitable for Bluetooth Low Energy. Like transmitting small volumes of data, such as sensor data, to smartphones

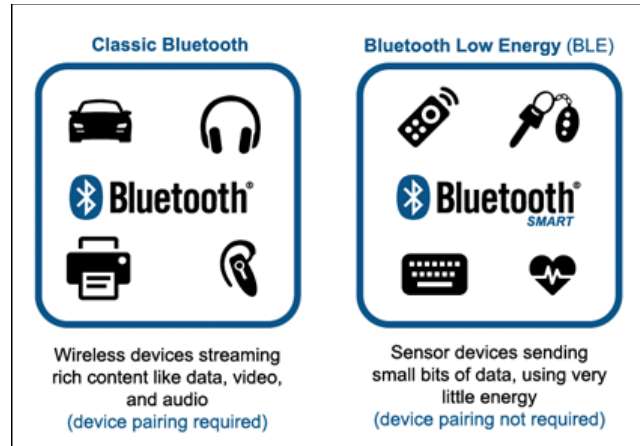


Figure 24: Classic Bluetooth and Bluetooth Low Energy

6.2.2. Why use the BLE module

We choose to use the BLE modules based on the following aspects. First, the BLE modules can perform stable data transmission under low power consumption. Second, getting the official technical specification document is easy, unlike other technologies' membership requirements. Third, BLE modules are getting cheaper, reducing developers' costs.

We first use the Adafruit BLE module; however, it cannot support 57600 baud rate communication with the TGAM chip. Therefore, we choose another BLE module: RN4870. The RN4870 can be easily configured and change the baud rate by entering its command mode.

6.2.3. RN4870 Features

- Onboard Bluetooth 4.2 low energy protocol stack.
- ASCII command interface API via UART.
- Scripting engine for off-host operations.
- UART Transparent Services for Serial Data Applications.
- Wireless remote configuration.
- Operates in ISM band 2.402 GHz to 2.480 GHz.

- Channel: 0-39.
- Receive Sensitivity: -90 dBm.
- Transmit power: 0 dBm.
- GAP, GATT, SM, L2CAP, and integrated public profiles.
- Software configurable for peripheral/central and client/server roles.

6.2.4. RN4870 Configuration Procedure

The RN4870 chip needs to be configured with specific settings before using it. First, wire chip like this: Vcc pin to 3.3V power, ground pin to ground, the P2_0/MODE pin (pin 18 on RN4870) to 3.3V, and TX/RX to the computer. Then, set the Coolterm software baud rate to 115200 (because the factory setting for this chip is 115200). Next, type “\$\$\$” into the Coolterm terminal and get the response “CMD>” in the terminal, which means the chip is in command mode and types the command listed in the user guide to make it achieve multi-functions. For the final purpose, the UART data from the TGAM chip needs to be converted into a Bluetooth LE signal which the computer can use. To do so, follow the instructions in the RN4870_setup_instruction.txt file. The RN4870 chip only needs to do the setup once, and the settings are preserved after powering off.

6.2.5. Wireless Data Transferring

- Windows:

Windows have its API for handling Bluetooth communication for working with Bluetooth. Through our research, we first came across a repository by Microsoft that shows their API for Bluetooth LE. However, it's written in Csharp and Cppwinrt, which I'm unfamiliar with. There is also an old example written in C, but it is only for classic Bluetooth.

- macOS:

macOS uses CoreBluetooth as its embedded Bluetooth module. We also found a repository for that, which is written in Objective-C. Someone also wrote a package called BabyBluetooth that makes the API much easier to use, but it is also in Objective-C.

- Linux:

Bluez is the Bluetooth protocol stack for Linux. It is written in C and by far the easiest to use. We did manage to receive advertisements and make connections with multiple Bluetooth devices with this API.

- Python:

Python has Tons of packages that deal with Bluetooth LE, from focusing on embedded systems to offering cross-platform supports. The one used in our product is Bleak, an open source, an easy-to-use python package that provides support for Windows, macOS, Linux, and Android.

- Bleak:

Bleak (short for Bluetooth Low Energy Platform Agnostic Klient) is an open-source python package that handles Bluetooth Low Energy communication across multiply platforms. It has an easy-use API and decent documentation. We use the bleak API to discover Bluetooth LE devices, establish connections, and get notifications (data). The latter part of this report will explain how to use bleak in this project. (<https://github.com/hbldh/bleak>)

6.3. Parsing Data

Data output from the TGAM chip is in the form of data packets, and we need to parse the packet to get the data being transmitted. Narosky, the company that designed the TGAM chip, provided some example code in C to parse their data packets.

(http://developer.neurosky.com/docs/doku.php?id=thinkgear_communications_protocol)

In general, the program can take either Bluetooth LE data stream or a file of recorded data in txt form and produce a list of CSV files all in a folder. The files contain date-time stamps, raw wave data, and anything motioned in the TGAM communication protocol. You can take that data and stick to any analysis software. You can also choose to produce a simple plot from the data collected inside the program.

The code repository has detailed instructions and explanations on how to set up the whole experiment and debug things.

The code is available for future developers on this project's GitHub repository.

(<https://github.com/Lehong-Wang/Simple-EEG-Project-based-on-Bluetooth-LE-and-RN4870-and-TGAM>)

Experiment setup procedures

- First step: Getting components
 1. TGAM chip
 2. RN4870 chip
 3. 3.3V power supply
 4. Wires

5. Computer with Bluetooth LE support

- Second step: Hardware preparation

This step is to set up and wire up the two chips. First, configure the RN4870 chip according to the “RN4870 configuration procedure” part mentioned above. Connect both to a 3.3V power supply, connect the TX pin of TGAM to the RX pin of RN4870, connect the EEG electrodes, and stick to places on your head; the system should be streaming out EEG data through Bluetooth LE signals. The next step is to receive the signal on the computer.

- Third step: Computer setup

This step is to set up the computer for receiving EEG data and processing them. First, set up a python programming environment and download this repo to your computer. You can install the dependencies by “pip install -r dependencies.txt.” This will install the dependencies from dependencies.txt. If this doesn’t work, you can manually install the packages with “pip install bleak” and “pip installs matplotlib.”

After the environment is setup, open the get_characteristic.py file and uncomment the “asyncio.run (timed_scan_ble ())” link at the bottom to scan for your RN4870 device. It should show up as RN_BLE or something similar.

```
0B5049C5-F505-25FE-4E35-8C9E5B2CA860: Unknown  
51144FC6-5C22-CCF6-AAF9-A5F20B95FE3C: Unknown  
FFCF4AB4-4E1D-0ADD-28B3-A9FE4C1D1427: Unknown  
69387122-FD9B-B514-FAD9-D01F7A84A6C9: Unknown  
A46EB02C-7B16-0696-8ED6-9F5679DE8270: RN_BLE ←  
FAE174AB-E09D-6F49-E0B9-6F6D96412B59: Unknown  
E94791DB-AC81-70B3-A3C6-D5C2F9402142: Unknown  
364DAF12-92AD-2713-387D-2D1C0BC23491: Unknown  
37D44FFF-80B7-E69F-7614-0967384981FF: Unknown
```

Figure 25: The pointer showed the device address and name of the RN4870 chip

Copy the device address into the ADDRESS variable at the top of the file and uncomment the “`asyncio.run (timed_scan_characteristic ())`” line at the end of the file to get the characteristic UUID for the RN4870. Find the first characteristic and copy that. (If first one doesn’t work, also try the others)

```
if __name__ == "__main__":  
    ## Uncomment this line to scan for Bluetooth LE devices  
    # asyncio.run(timed_scan_ble()) ←  
    logging.basicConfig(level=logging.INFO)  
    ## Uncomment this line to get the characteristic of the given device address  
    # asyncio.run(timed_scan_characteristic()) ←
```

Figure 26: The pointers show the two lines of code mentioned above

Go to the `get_notification.py` file, and at the top, fill in both device address and characteristic UUID, and run the file. It should start connecting to RN4870 and receiving data. To set the data recording time, change the `RECORD_TIME` variable at the top of the file.

At the end of the recording, find a folder called `parse` being created, which contains EEG data. Although there is an upper limit on how many lines there are in a file, it can be customized by changing the `MAX_ROW_PER_FILE` variable at the top of the `parse.py` file.

- Fourth step: simple data visualization

Finally, to produce a simple visualization for the data, use the function at the bottom of the `get_notification.py` file: “`generate_graph (field_x = "Time", field_y = "Raw_Wave")`”. Which can produce different axis by changing the `field_x` and `field_y` variables. A list of options is listed there as well. However, the plot function is not bringing enough efficiency at handling a large amount of data. If want to plot the “`Raw_Wave`” value, do not trying to plot a data set records over 15 seconds, which could take a significant amount of time.

6.4. Debugging and Troubleshooting

(The detailed debugging guide is in the repository mentioned above.)

- TGAM chip not working at a baud rate of 57600:

TGAM chip should work at 57600 by default, out of the box. If it's not the case, you may want to refer to the "Configurable Default Settings" section of the TGAM data sheet linked above.

- RN4870 chip not working:

If the system is not working in terms of not being able to receive data on the computer side, then there are a few things you can do to troubleshoot:

- Check the wiring. This might seem dumb but check the wire connections and power supply. Our team was stuck on this problem for a long time because our power supply was not good.
- Go through the debugging guide carefully, and there are several steps you can follow to find where the problem is and fix it.

7. Enclosure Design

7.1. Criterion

7.1.1. Technical Support

Patch design needs to meet the size of the TGAM board (3cm x 3cm). In addition to accommodating the PCB, all wires should be attached to the patch in a recessed form. To help the placement of the TGAM board, the patch needs to be designed to open and close so that it does not open when closed due to any other accidental factors by using enclosures. In order to

detect the data, three-electrode holes need to be reserved on the patch to be connected by wires. Finding the right location is also a consideration.

As shown in the figure below, conventional EEG instruments require the user to make extensive use of small metal discs, or electrodes, attached to the scalp to detect data. We choose to design the ear EEG by reconsidering where the electrodes are located.



Figure 27: Example of traditional EEG electrodes placement

7.1.2. Design Functionality

As a device that can be used by the public, patch design needs to be able to make the user understand how to use it at once. To put it simply, it is easy to understand and easy to understand at a glance. In order to ease the user's use, the design of the patch needs to fit the user's user experience as much as possible. As an ear EEG, it is important to minimize the discomfort of the user in wearing the product and the error caused by the detection data (MKnierim, 2021). We should minimize the contact area between the patch and the user's skin by using softer materials. To facilitate the change, we chose 3D printing as our current factor for assessing the feasibility of the patch design.

7.1.3. Initial idea

Here is our simplest version for the patch design. As an ear EEG, there are two ideas: one is embedded, meaning that the instrument will be placed directly in the inner ear to detect data. The other one is hanging ear type, which means that the device will hang at the ear and monitor the data in the outer ear. The advantage of an inner ear device is that we can store all the wires inside

the device. This is a good wire arrangement, but the problem is that the embedded type will bring more discomfort to the user and the higher sensitivity level will lead to data bias. And the size of the PCB we designed would not fit in the inner ear. So, we opted for an ear-mounted design. Our idea is to prevent the instrument from falling down by the structure of the instrument itself catching on the ear. Since the measurement required three electrode holes, the PCB was set directly behind the ear. We did not draw the cable channels and interfaces because we just wanted to make sure that the holes for the electrodes and the size were appropriate.

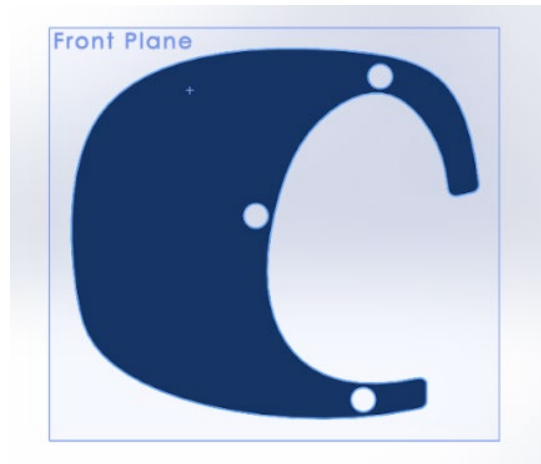


Figure 28: Initial version of the enclosure design

7.1.4. Reduce contact area & improve the effective use of space

Since the patch sticks to the skin, we have dropped the design that wraps around the upper ear. Enough space is reserved for storing circuit boards, etc. In this design, we thought a little



Figure 29: Wearing test of inside and the outside of the ear

about how the electrodes will connect with the circuitry. We left a clear path from the electrode holes to the “landing pad” for the chip and battery.



Figure 30: Enclosure design after improving the effective use of space

7.1.5. Fine-tuning

For our next stage, we did some heavy lifting. We added a second layer, wire channels, adjusted the size of the circuit board spot, and made a built-in rounded “bump” that looks nice and is intended to hold the battery. The second layer was put in place to make the design one piece instead of having a removable chargeable battery enclosure. The wire channels are to make sure the electrodes go unseen. Upon review, we realized each layer was too thin and flimsy as well as the housing was not big enough to have all the circuitry.

7.1.6. Add enclosures

Our next design has us coming closer to the finish line. First, we started with some issues from the last design, including changing the thickness of the top 2x bottom to 1.5x and removing the wire channels from the top half. We then had to think about a way to hold the two patch halves together. We started with two different solutions: the hooks and the pressure bump. The hook solution consisted of adding small “hooks” on the bottom patch that prevented the patches from sliding apart. The pressure bump solution involves putting a small protrusion on the bottom

patch that matches a hole on the top patch. We angled the protrusion outward as it went up so when we put the two patches together, the pressure bump held them there.

The bottom half of the hook version. Had another version with 2 hooks but had to increase the hook amount to prevent unwanted sliding.

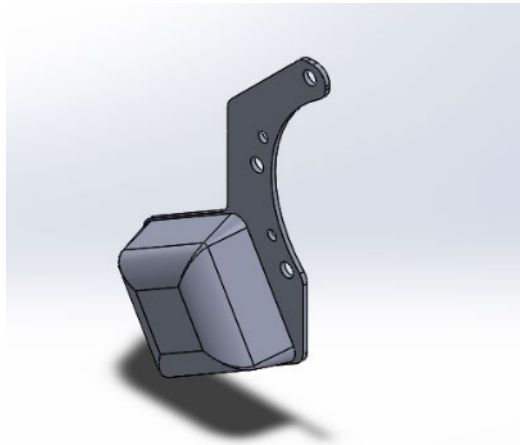


Figure 31 Top and bottom of pressure bump version. Has 2 bumps to prevent rotation.

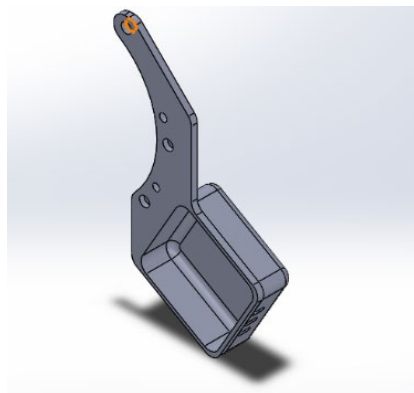


Figure 32 The bottom half of the hook version. Had another version with 2 hooks but had to increase the hook amount to prevent unwanted sliding.

7.1.7. Update enclosures

In the next update, we did narrow it down to one solution. We improved on the pressure bump strategy and added a

second bump. We also changed the design of the bump to be squarer and have less extra room. Other changes include making the top half thicker to cover up the caps, putting the three contacts for charging on the bump



electrode

Figure 33 Final top half with bumps, changed contact location, increased thickness, and adjusted bump shape

instead of on the bottom patch, and slightly adjusting the bottom thickness and pressure bump hole size.

8. Experimental Group

In this IQP project, we designed our own ear-based EEG device. Team was divided into three groups, which were responsible for the software, the board design, and the experimental group. As the experimental group, we worked on the ear EEG patch design by learning how the brain's nervous system works, how EEG imaging functions, and how to measure and observe the data.

For data collection initially, we used a BioSignals Plux module.

[\(<https://www.pluxbiosignals.com/collections/shop/products/researcher-kit>\)](https://www.pluxbiosignals.com/collections/shop/products/researcher-kit)

- two measurement electrodes, detect the electrical potentials in the specific stomach region of choice.
- one reference electrode, placed in an area of low bioelectrical activity.

8.1. Electroencephalography Learning

9.1.1. Electroencephalography (EEG)

Electroencephalography (EEG) is an electrophysiological monitoring method for non-invasive recording of brain electrical activity, where electrodes are placed along the scalp and then the electrical activity of the brain spontaneously performed over some time is recorded through multiple electrodes placed on the scalp. It is used clinically in the diagnosis of epilepsy, sleep disorders, depth of anesthesia, coma, encephalopathy, and brain death, on the one hand,

and in the field of experimental psychology to provide a tool for brain activity and is also a neuroimaging method that is widely used in computational neuroscience.

9.1.2. Bioelectricity

Bioelectricity is the change in electrical potential and polarity that occurs in the organs, tissues, and cells of living things during their life activities. It is a fundamental feature of life activity, from the whale to the cell, and all have strong or weak bioelectricity.

The concept of bioelectricity is very different from that of electric current, which is generated by the movement of electric charges, while bioelectricity in living things is the presence of some special channels in the cell membrane. When the concentration of ions inside and outside the cell membrane is out of balance, the special channels in the cell membrane will open, so that the ions of sodium, potassium, and calcium flow into the cell from outside the cell membrane or out of the cell, thus forming bioelectricity. Without this bioelectricity, no living creature could have any life activity.

The essence of EEG is a form of bioelectricity, which was first recorded in 1924 by the German physiologist and psychiatrist Hans Berger (1873-1941), who recorded the first human EEG. Berger's invention of the EEG, which has been described as "one of the most surprising, remarkable, and important developments in the history of clinical neurology," was an extension of previous animal studies. It was they who pioneered the EEG and henceforth started the long road of its development.

9.1.3. Anatomy of the Cerebral Cortex

The surface of the brain has many sulci and gyri, which divide the brain into four brain regions: the central sulcus, parieto-occipital fissure, and lateral fissure divide the brain into

frontal, parietal, occipital, and temporal lobes. The temporal lobe is dominated by auditory functions, the occipital lobe by visual functions, the parietal lobe is the higher center of somatosensory functions and the frontal lobe by somatic motor functions. The contact area between the prefrontal cortex and the temporal, parietal, and occipital cortices is related to higher brain activities such as complex perception, attention, and thinking.

The thickness of the cerebral cortex is 2.5 mm on average, and the outermost layer is a dark structure, which is the cell body of the nerve cell, also called gray matter, and the area where we collect EEG signals; the structure below the cortex is the axon of the nerve cell, whose role is to transmit signals from the neurons in the cortex, and it is also called white matter because the axon is wrapped by a lighter colored myelin sheath. The higher center that governs our actions is the cerebral cortex, also known as the gray matter. The bioelectricity that can be captured by EEG is the firing of neurons in the gray matter, which allows us to explore the workings of the gray matter.

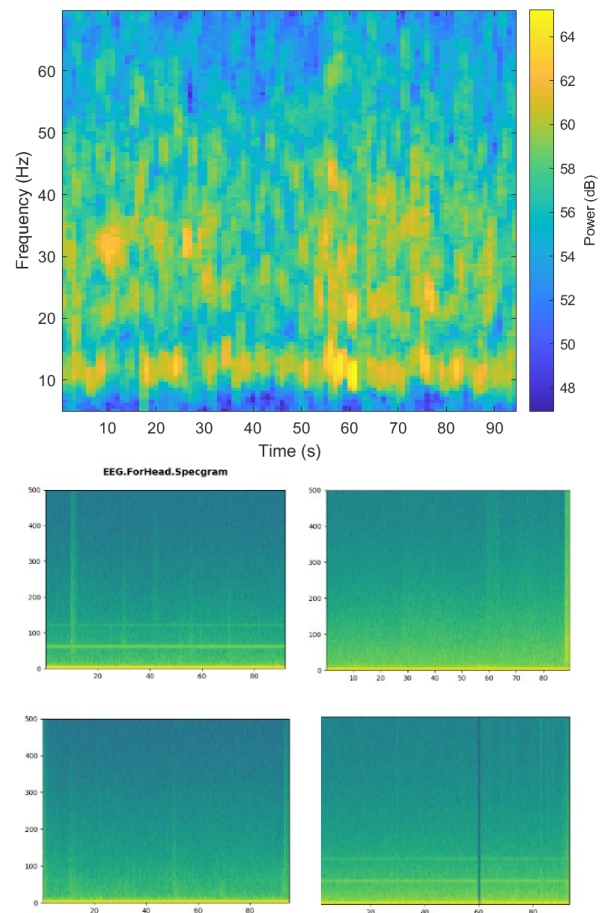


Figure 34: An example of messy EEG data. There is a band at 10 Hz present which is characteristic of having eyes closed, but there is too much noise and the band lasts for when the subject had their eyes open.

9.2. Electrode Position Test

Ear EEG is much less intrusive than the typical solutions for collecting EEG data (electrodes on the scalp). Ear EEG consists of fewer electrodes, fewer wires, and a lower setup time (Meiser, 2020). However, collecting EEG data from the ear presents several challenges in the data collection, primarily where to place the electrodes for the best signal, and reduced sensitivity to certain kinds of brain activity. There are primarily two styles for ear EEG: in-ear and around the ear. In-ear EEG consists of electrodes mounted on an earbud-style device that is coated in the conductive gel. Around the ear is slightly less intrusive and is the style we used. Specifically, we used 3 different electrodes around the outside of the ear on the head. We placed one at the top and one at the bottom of the ear (the primary electrodes) and one in the middle directly behind the ear (reference electrode) (Choi, et al., 2018).

9.2.1. Increase the Distance Between Electrodes

The two wires with the black and redheads are the main electrodes, and the white head is the reference electrode. In order to have the two main electrodes in as different positions as possible, we set them one at the top behind the ear and the other near the back of the earlobe, respectively. The reference electrode we set up near the neck to allow for more placement. Since the electrode patch was too big, we cut the foam part leaving only the gel part. However, since the gel was not sticky enough, we added it firmly behind the ear by using a crossover.

9.2.2. Inside the Ear or Outside the Ear?

Due to uncertainty as to which location would yield the most stable data, we set one primary electrode inside the ear and the reference electrode at the earlobe. This method was abandoned by us due to the location as it was too uncomfortable to collect data.

9.3. Experimental Process

In the experimental process, we tested the different positions behind the ear/head. Through research, we figured out the positions for electrodes that give us the highest resolution, primarily on the forehead () and behind the ears ().

Behind the ears, we figured that the best place to put the two non-reference electrodes was as far away from each other as possible around the ear (picture that

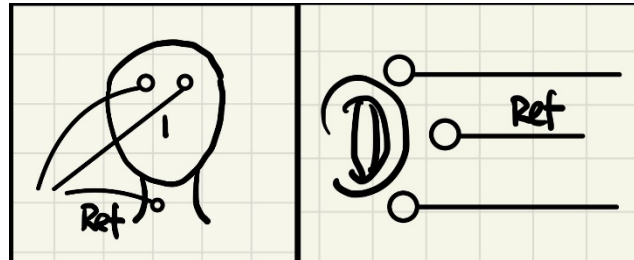


Figure 35: Forehead and behind the ears

shows distinct positions). On the forehead, there is plenty of space to separate the electrodes.

The data has a terrible resolution when the electrodes are placed on the forehead. It is extremely hard to figure out what is noise and what is meaningful data (data picture). The data from the forehead is also affected a lot more by blinking than behind the ears. When the electrodes are behind the ears, we get a change in the frequency band of 10 Hz when the person opens or closes their eyes for an extended period. This is the frequency of what are known as alpha waves (), which are prominent while the eyes are closed.

To reduce noise in our data, we employed several strategies. Wiping the skin with alcohol before testing was somewhat effective and gave us a cleaner difference between eyes open/closed. Cutting the foam monitoring electrodes to the smallest size helped as we were able to maneuver the electrodes into the hard-to-reach spot above the ear. After the data started looking acceptable, we changed from foam electrodes to wet gel radio-translucent electrodes, which are of higher quality. As well as every time we test, we use alcohol to wipe the test area to ensure the neatness of the skin.

9.4. Procedure for EEG data collection

9.4.1. Staggered Eye-opening and Eye-closing Test Method

In order to get some useful data, we decided to stage some actions to let the instrument analyze our changes. Trying not to use other muscles, we only made the instrument respond by stage blinking and closing our eyes.

With every electrode position:

1. Set up electrodes on the subject's head
2. Restart the biosignals plux module and the software on the computer
3. Ensure data is transmitting and wait 10 seconds after the initial transmission
4. Time 20 seconds the subject spends with their eyes open, keeping as rigid of a facial expression as possible
5. Time 20 seconds the subject spends with their eyes closed, keeping their face rigid
6. Time 20 seconds the subject spends with their eyes open, but this time relaxed and taking deep breaths
7. Time 20 seconds the subject spends with their eyes closed, also relaxed
8. Finish data recording

9.4.2. Extension of Divergent Phases

From the inconspicuous data above, it appears that we were too active at different stages. Not enough for the device to get more effective data, so we increased the time spent in each phase in the hope that it would improve.

With every electrode position:

1. Set up electrodes on the subject's head
2. Restart the biosignals plux module and the software on the computer
3. Ensure data is transmitting and wait 10 seconds after the initial transmission
4. Time 60 seconds the subject spends with their eyes closed, maintaining as rigid of a facial expression as possible
5. Time 60 seconds the subject spends with their eyes closed, keeping their face rigid
6. Finish data recording

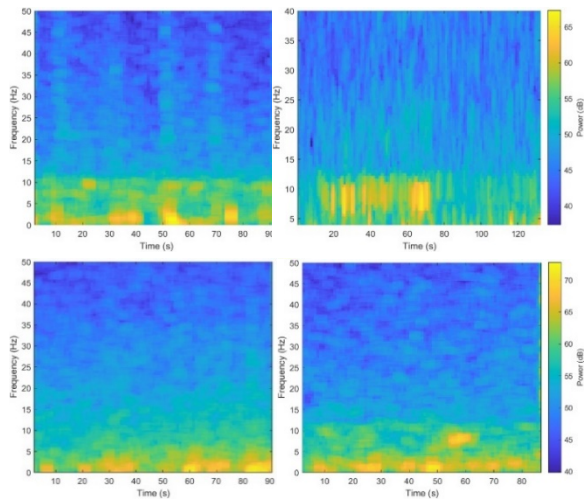


Figure 36: This figure shows an example of clean EEG eyes open/closed data. Between 10 and 70 seconds (when the subject's eyes are closed), there is a band at 10 Hz, known as alpha waves. These are very well-documented in EEG as a present while eyes are closed.

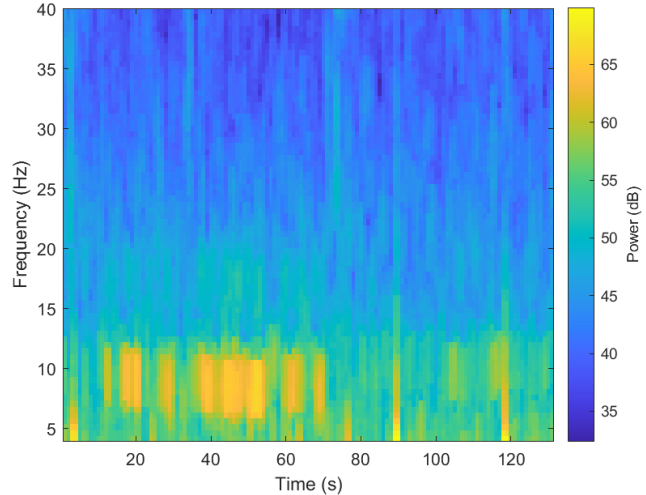


Figure 37: Another (mostly) clean EEG data graph

10.Future Work

10.1. Hardware

For the future development, we plan to design a charger and charging circuit on the PCB to test its functionality. We also plan to finish the detachable electrode wire design, extending metal pins from the PCB to the outer edge of the enclosure so that we can make the entire enclosure detachable from the patch. Besides that, we need to work with the test team to monitor the noise during the use to see if we need to improve the circuit design to achieve less noise.

10.2. Software

An easy-to-use data parsing software is vital for future work. For the next step, we plan to finish the data parsing and Bluetooth connection code encapsulation. Furthermore, we plan to upgrade the existing prototype to develop a market-level device. The device will be a non-invasive self-active BCI that can improve sleeping quality. We will create a reinforce-learning algorithm for appropriate interventions when monitored sleep spindles perform abnormally. The system will be cloud-based, using cloud computing for data processing and a cloud database for storing user information.

10.3. Enclosure Design

In order to create a more comfortable and better experience for customers, the final design will be optimized in addition to the material. We also want to optimize the wiring of the electrodes. We plan to make the enclosure completely wireless by combining it with the PCB part. Another prospective is that, we are testing only the enclosure for adult ears, and later we will design it for infants, children, teenagers, and the elderly. Our goal is to make our products cover all age groups.

11. Conclusion

As we reach the end of the summer, after working on this project for several months, we all get familiar with the product development process and have a deeper understanding of BCI and EEG device. The work we've done for the past few months can be valuable reference for future developers. We believe the EEG device we are building has a promising future and will eventually revolutionize similar products on the market. We also envision that other functions will be developed upon our design EEG device with wider range of using scenarios to eventually help more users achieve healthier and better life.

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