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Design and Development of a Wireless EEG System Integrated into a Football Helmet

Akshay V. Dunakhe
University of South Florida, avdunakhe@gmail.com

Design and Development of a Wireless EEG System

Integrated into a Football Helmet

by

Akshay V. Dunakhe

A thesis submitted in partial fulfillment
of the requirements for the degree of
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Co-Major Professor: Anna Pyayt, Ph.D.
Co-Major Professor: Stephen E. Saddow, Ph.D.
Sylvia Thomas, Ph.D.

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DEDICATION

I dedicate this work to my loving parents and my younger brother who supported me constantly and unconditionally throughout my graduate studies.

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ABSTRACT

In the United States, approximately 2.8 million Traumatic Brain Injuries (TBI) occur annually. Out of these 2.8 million occurrences, 280,000 injuries are caused by sports and recreational activities. The actual number can be significantly higher since mild TBI are often unrecorded. These injuries not only cause physical damage to players, but they are also one of the leading causes of a player's retirement from a sports career. While working with TBIs, it is vital to detect the concussion at its first occurrence, termed as a "primary concussion." If the primary concussion goes undetected, the player may continue to play the game, which makes the player highly susceptible for a secondary concussion. Secondary concussions may lead to "second impact syndrome" which is a major cause of deaths resulting from TBI. Thus, it is vital to precisely detect and diagnose primary concussions within strict time constraints. Currently, Symptoms Check Lists are used as a tool to assess head impact for the possibility of concussion occurrence. Apart from Symptoms Checklist, the Computerized Tomography (CT), Magnetic Resonance Imaging (MRI) scans and standardized EEG tests are used for advanced assessment and diagnosis of a brain injury. The symptoms checklist can only provide the likelihood of a TBI occurrence upon sustained head impact. On the other hand, imaging tests are typically carried out using the advanced medical diagnostic equipment which are available only in hospitals and specialized labs. Hence, state of the art techniques used for brain function monitoring fail to provide real-time detection and diagnosis of a TBI. To counter this issue, we propose a novel system which can monitor the EEG signals of a user in real-time and alert a sports physiologist of any significant disturbances in EEG signal characteristics upon sustaining a head impact event. Even though the developed system is

still in the design prototype stage, upon integration as a whole system, the proposed system can be a promising step in real-time detection and diagnosis of a primary concussion in sports players. This is, especially true for American football players who are known to suffer multiple events such as this, often without any awareness to either themselves or their health care professionals. Thus this system has been specifically designed for use by American football players and is to be integrated into their helmet, thus allowing for real-time detection of TBI.

CHAPTER 1:

INTRODUCTION

Traumatic Brain Injuries (TBI), are injuries caused by either a direct or indirect blow to the head and, are one of the primary causes of death in the United States of America [1]. The Centers for Disease Controls and Prevention (CDC) states that, in 2013, TBI contributed to 2.8 million cases of the total injuries recorded [1]. Table 1 represents the statistics related to TBIs. These numbers listed may be low due to the fact that often these types of injuries are undetected.

Table 1: Statistics of traumatic brain injuries in 2013[1]

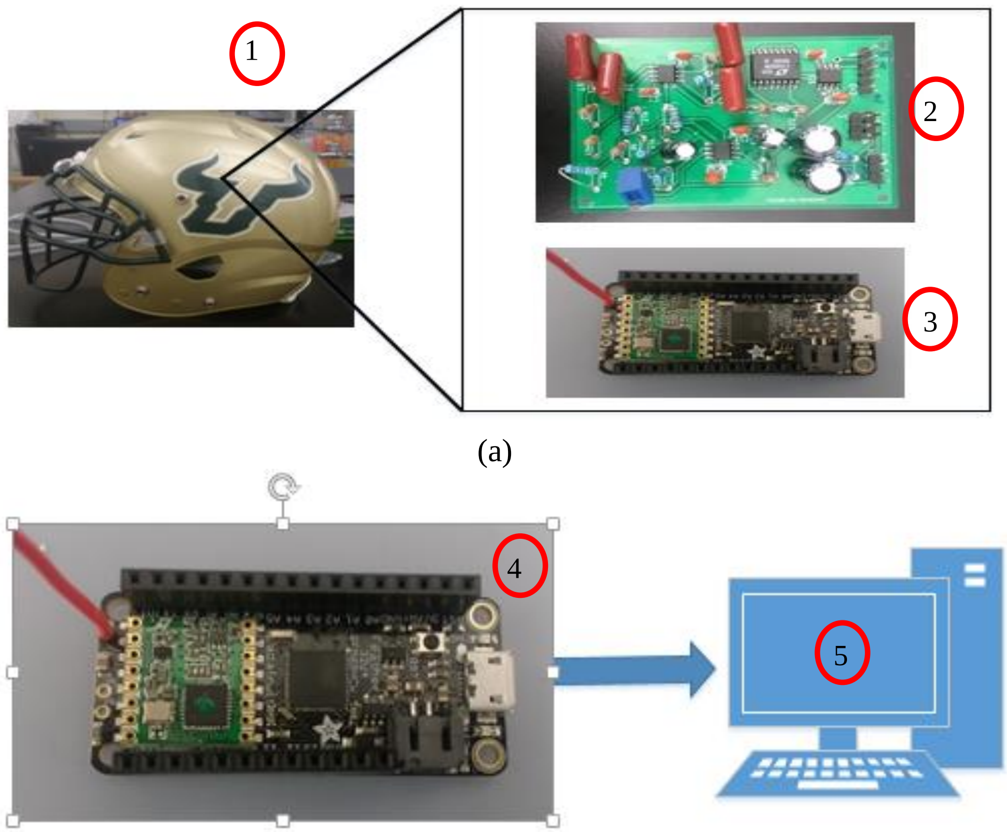
Sr. No.	**Facts**	**Statistics**
1	Total TBI reported	2.8 million
2	Deaths caused by TBIs	50,000
3	Leading cause of TBIs	Falls (47%)
4	Second leading cause	Being stuck by or against an object 420,000

Most of the sports-related injuries are categorized as mild traumatic brain injuries. These statistics became the motivational force behind developing a novel system which can detect the changes in regular EEG waveforms within the first moments of their occurrence; which, in turn, can be used as a detecting tool for the possibility of mTBI (alternatively known as Concussions) in American Football players.

The leading cause of mild traumatic brain injury, as the name suggests, is the impact sustained by the brain, which results in abnormal functioning lasting from a few days to several years. Being a victim of TBI can be disastrous for a player since, in most of the cases of concussions, players end up terminating their sports career or committing suicide as a result of depression. These brain injuries can be diagnosed using various high-end imaging technologies such as MRI and CT scans. However, these techniques fail to reduce the damage and emerge as prime techniques to detect the TBIs on-site. The shortcomings are mainly due to two reasons. Firstly: it is not always possible to have a CT scan or MRI equipment on site, and secondly: concussions do not normally reflect any significant physiological symptoms immediately after the impact. Thus such injuries go undetected and undiagnosed. Also, for every single player, the threshold to withstand a head impact without showing any profound effects on health can be different, and hence it becomes even more difficult to detect whether the player has sustained a concussion or not. For all these reasons, the use of high-end imaging techniques results in a lack of real-time, accurate detection leading to delayed diagnosis.

In addition to the above-mentioned limitations of advanced imaging techniques, the nature of a concussion proves to be the major obstacle in its accurate detection and diagnosis. If the player sustains a blow to the head resulting in a primary concussion but does not show any prominent symptoms, it is possible that the player will continue to play the game. If the player continues to play the game with a primary concussion, he/she is highly susceptible to a secondary concussion. The secondary concussion can result in a condition known as "second impact syndrome." Second impact syndrome is when a patient sustains a second blow to the head within a very short time period from the first impact, or when the first concussion has not completely healed[1]. This condition is known to cause an increase in intracranial blood pressure and vascular congestion[1]. This condition may ultimately result in the death of the patient.

To counter the shortcomings mentioned earlier, we came up with a novel system which can monitor real-time EEG signals without a physical connection between the user and the monitoring station. This system makes use of an EEG signal from a user, and with the use of further signal processing, a noise-free signal is transmitted to the remote monitoring station. The proposed system is divided into three units, and two these units are mounted inside the player's protective helmet. These are namely the EEG signal detection and processing unit, the signal transmission unit and the third unit is located at the physician's desk, namely the Signals receiving unit as shown in Figure 1. As the proposed system can be fitted inside the helmet, it offers benefits such as ease of movement, reduced hardware to carry on the head and ease of recording EEG signals.



(b)

Figure 1: (a) Wireless EEG system – Helmet system. Legends: 1 – Football helmet, 2 – EEG board, 3 – Wireless transmitter (b) Wireless EEG system – Receiver system. Legends: 4 – Wireless receiver, 5 – Monitoring system

The overall organization of this thesis is as follows; the first chapter introduces the problem, the primary causes of TBI and measures to counteract it. In the second chapter, various aspects of an EEG signal are discussed. The third chapter includes the system design approach used. The last two chapters summarize the results obtained and the methods used to verify the obtained results as well as the conclusion and future scope.

1.1. Definitions and Classification of mTBI

We can define Traumatic Brain Injury (TBI) as the injury caused to the brain in the events of the transfer of traumatic force to the brain from body parts such as the skull and neck. Mild Traumatic Brain Injury (mTBI), or concussion, is a prevalent cause of critical and potentially permanent damage to the brain as well as retirement among American Football players. A more formal definition of traumatic brain injury is presented by the Center for Disease Control (CDC), which is, “A disruption in the normal function of the brain that can be caused by a bump, blow, or jolt to the head, or penetrating head injury[1]".

TBI can be broadly classified into three main categories as follows:

- Mechanism: This category defines whether the injury is a closed-skull or an open skull injury. Most of football related TBIs fall under the closed-skull injury category.
- The scale of the Outcome: This category deals with the effects of an injury on the brain, and their outcomes.
- Severity: It includes the measure of severity of the injury.

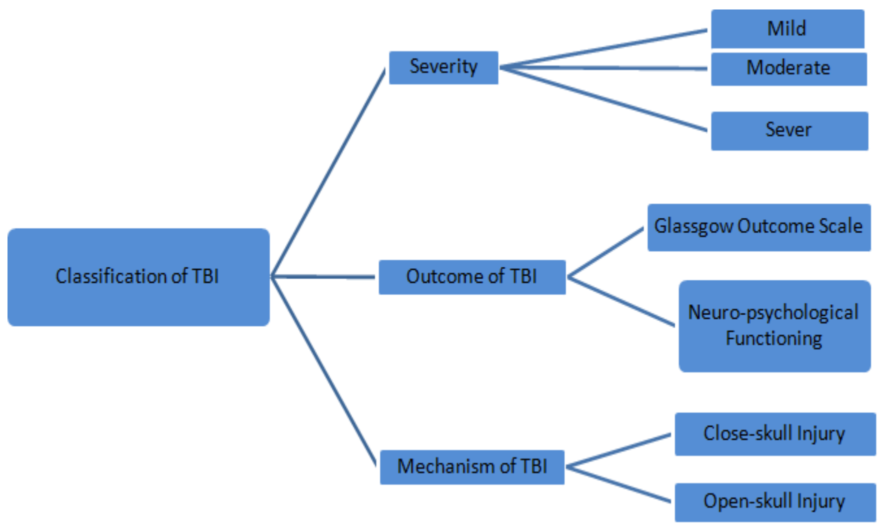


Figure 2: Classification traumatic brain injuries

As most sports-related brain injuries are intact-skull mild traumatic brain injuries, the player barely shows any significant symptoms of injury. Hence such injuries go undetected most of the time. Also, as far as, sports injuries are concerned, it is not always possible to use high-end techniques such as MRI and CT-Scans to diagnose TBI. To overcome this issue, researchers are working on a nascent methodology which involves the use of a quantitative-EEG(q-EEG).

1.2. Traumatic Brain Injury Detection: State of The Art Techniques

To assess various aspects of brain injury such as its occurrence, severity, and consequences, currently there are numerous methods are in use. This section discusses various perspectives of existing methods and technologies used to assess traumatic brain injury.

1.2.1. Sideline Assessments: Non-Hospital Assessment Methods

1.2.1.1. Neurocognitive Testing

Neurocognitive testing is achieved in two stages throughout the football season. The first stage consists of a pre-season examination of the player. In the pre-season exam, the player is tested for cognitive functioning. As this test is conducted before the start of the season it is termed the ‘baseline neurocognitive testing.’ The results of this test serve as a ‘reference’ or ‘baseline’ for tests conducted during the season. Such evaluation helps to determine if the player has any pre-existing cognitive dysfunctions that may affect the assessment of results of post-traumatic tests. The second stage of this test is conducted during the season, i.e., after the player sustains trauma to the head. This part is termed as the "neurocognitive test" which tests the thinking and reaction ability of the player.

1.2.1.1.1. Paper and Pencil Method

It is one of the most efficient ways of assessment of the post-traumatic concussion in a way that, this method can quantify the severity of the injury and eliminate the need of some of the guesswork during the assessment[4]. In this method of assessment, various cognitive functions are examined such as short-term and working memory, concentration, information processing time and reaction time[4]. Since the outcomes of these tests are based on the results of the baseline test, the accuracy of pre-season baseline test results will decide the accuracy of post-traumatic test results.

Table 2 represents the various tests conducted to examine different cognitive functions of the brain post trauma[4]. The Controlled oral word association test and Hopkins verbal learning tests are the tests related to lingual functions of the brain. The Trail making test, Wechsler digit span, and Stroop color-word test are carried out to test the attention and motor coordination of a subject.

1.2.1.1.2. Computerized Neurophysiological Test

Even though the traditional methods of cognitive functioning are efficient, the computerized test has its advantages in addition to the pen and pencil test. In these types of tests, a patient is presented with a set of various tasks and the reaction time, as well as various other neurophysiological functions, are tested with an automated software program.

There are numerous algorithms used for computerized cognitive function testing and these have been validated for use in sports set-up. A few of these are listed below:

Table 2: Neurophysiological tests used to assess concussions[4]

Neurophysiological Test	**Cognitive Domain**
Controlled Oral Word Association	Verbal Fluency
Hopkins Verbal Learning Test	Verbal learning, immediate and delayed memory
Trail Making: Parts A and B	Visual scanning, attention, information processing speed, psychomotor speed
Wechsler Letter-Number Sequencing Test	Verbal working memory
Wechsler Digit Span: Digits Forward and Digits Backward	Attention, Concentration
Symbol Digit Modalities Test	Psychomotor speed, attention, concentration
Paced Auditory Serial Addition Test	Attention, concentration
Stroop Color Word Test	Attention, information processing speed

1. Immediate Post Concussion Assessment and Cognitive Testing (ImPACT) developed at the University of Pittsburgh Medical Center[4].
2. Computerized Cognitive Assessment Tool (CCAT) [4].
3. Concussion Vital Signs - a web-based neurocognitive assessment platform developed by CNS Vital Signs and marketed by Pearson, which provides a brief, web-based neurocognitive baseline, and post-injury testing solution, a self-reported history, mobile-deployed sideline assessment, and a post-concussion symptom checklist[4].

Some of the identified, compelling advantages of this method of cognitive testing are rapid scoring, ease of administration, increased test-retest reliability, greater accessibility.

1.2.1.2. Symptoms Checklist

Checklist of symptoms is another powerful tool used to determine whether the athlete has sustained a concussion or not. This checklist is composed of various symptoms related to neurocognitive dysfunctions and the score of an athlete for that particular symptom. In general, there are two most commonly used approaches of symptom checklist, which are: timeline approach and occurrence-of-symptom approach. The first approach determines the score of a symptom-based on its occurrence in regular time intervals, and the second approach involves scoring of a symptom-based on how rarely or frequently the particular symptom occurs. Appendix A contains a symptom checklist by CDC.

1.2.2. Clinical Evaluation: A Hospital-Based Method

1.2.2.1. Imaging Techniques

The various methods of evaluation of a traumatic brain injury are carried out away from the field, in a clinical set-up and by highly trained clinical staff. The Computerized Tomography (CT) scanning and Magnetic Resonance Imaging (MRI) techniques are the most commonly used imaging techniques for TBI evaluation purposes. With their ease of access to the emergency room, these techniques have a prevalent use for this purpose. This section explains the basic concepts behind their operation.

1.2.2.1.1. Computerized Tomography Scanning (CT Scanning)

The word 'tomography' in Computed Tomography is derived from the Greek word 'tomos' which means 'to write a slice or section[5]. The two significant limitations of X-ray imaging technique in the imaging of internal body structures led to the development of the CT scanning technique.

Figure 3: A CT scanner[5]

These limitations are:

1. In traditional X-ray imaging technique, the difficulty of diagnosis increases as three-dimensional information is superimposed on a single imaging plane; this makes the diagnosis very complicated and confusing.[5]

2. Because of the limited dynamic range of the photographic film used, only objects with higher variations in X-ray absorption with their surroundings, such as bones and cartilages, cause sufficient contrast on the photographic film.[5]

Hence, traditional X-ray has little or no significance while imaging the brain due to its protective, dense covering - the skull bone. On the other hand, CT scanners operate by rotating the X-ray tube, and photographic film around the patient. Thus there is always one imaging plane under the patient in the focus, and other planes are blurred out. “The pictures displayed are not photographs but are reconstructed from a large number of absorption profiles taken at regular angular intervals around a slice[5].”

1.2.3. Proposed System: Wireless EEG System

Modern medical and electronics technology enables the continuous monitoring of electrical activity from a patient's brain with the use of small sized, computer-based EEG monitors. Taking one step ahead, we developed an EEG monitoring device, able to collect EEG signal data continuously in real-time, and able to transmit it over the wireless communication protocol. This innovative technology combines the advantages of both concussion detection techniques mentioned above and combines them into a single wearable device. This system is capable of acquiring the EEG signal from an athlete who is involved in the rigorous physical activity and transmits this information to medical staff using wireless technology. The received EEG signal then can be monitored for any dominant changes in its characteristics.

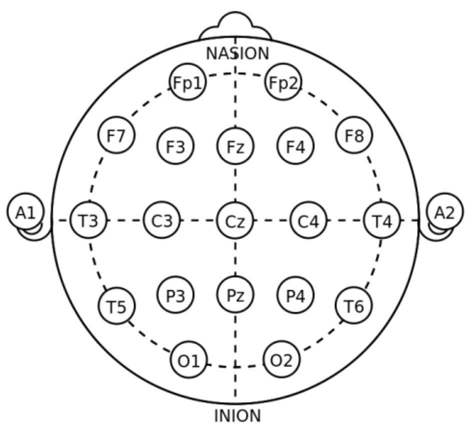


Figure 4: Standard 10-20 electrode placement system. Our system is a subset of this arrangement to allow for fast, real-time EEG recording during sports activity. Figure reused with permission. Published on Wikimedia Commons under public domain license. Refer to Appendix C

This method has some important advantages over traditional concussion detection techniques such as, real-time data collection and analysis: this feature eliminates the need of immediately transferring the player for clinical evaluation.

The wearable wireless EEG system allows free movements of a user while recordings are in progress, thus minimizing the interference of wires with the movements of an athlete.

1.3. Summary

This chapter discussed the gravity of the problem of mild traumatic brain injuries (i.e., concussions) in American football players. The victims of an mTBI, in most of the cases of sports-related concussions, do not show any prominent symptoms and also tend to avoid reporting the injury to the officials. Because of these reasons, the mTBI are left undiagnosed and thus result in serious health-related consequences. This chapter also outlines the importance of detecting the primary concussion in order to reduce health-related complexities in American football players. The first chapter summarizes the various tools and techniques used to detect and diagnose the mTBI and their limitations. In this chapter, the proposed system is introduced and is discussed in further chapters.

CHAPTER 2:

EEG AND ITS APPLICATION IN MTBI DETECTION

Electroencephalogram (EEG) - it is a record of a signal which is the addition of all the action potentials of neurons present in the brain. The firing of a single neuron produces an action potential (AP), and the measuring of a single AP requires the physical contact of the measuring device with the neuron of interest. However, when multiple neurons are triggered simultaneously, the resulting electrical activity is measurable with the use of surface electrodes.

As the neurons asynchronously generate the action potentials, the collective EEG signal forms an asymmetric, irregular wave-form containing various information about the neuron potentials**.** Hence, the EEG signal is stochastic in nature as opposed to the ECG signal [5]. These action potentials can be recorded collectively either at the surface of the scalp using surface electrodes or at the surface of the brain itself with the use of invasive electrodes. These recordings are continuous and oscillating in nature. The amplitude, frequency and morphological nature of a brain signal are primarily described by the brain functions carried out in various parts of the brain.

2.1. Characteristics of an EEG Signal

The frequency and amplitude characteristics of an EEG signal of a normal human being greatly depend on the functions of the cerebral cortex or the current mental state of that person such as various stages of sleep, level of attention, etc. The normal EEG signal has a frequency range between 0.5 Hz to 100 Hz and the amplitude varies from 2μV to 200μV [6]. The normal EEG can be classified into four distinct waveforms which are alpha (α), beta (β), theta (θ), and delta (δ).

2.1.1. Alpha Waves (α)

The alpha waves can be observed when a person is in a relaxed, quite, or relaxed-awake mental state. These waves can occur between the frequencies 8 Hz to 13 Hz and vary in amplitude from 2 μV to 200 μV [6]. These waves are the characteristics of the mind in an awake state but disappear completely when the subject under test falls asleep.

2.1.2. Beta Waves (β)

The beta waves in a normal, healthy person occur between 14 Hz to 30 Hz frequency range and with the amplitude of 5 μV to 10 μV. "They can be divided into two major types: beta I and beta II. Beta I waves have a frequency about twice that of the alpha waves. "They are affected by the mental activity in a similar way as that of alpha waves (these waves disappear completely and are replaced by asynchronous, low voltage wave). The beta II waves, on the other hand, appear during intense activation of the central nervous system and mental stress "[6]. From this behavior of beta waves, it is clear that the mental activity inhibits the one wave (Beta I) and the other wave (Beta II) is enhanced due to the mental activity.

2.1.3. Theta Waves (Θ)

The theta waves in adults characterize emotional stress. These waves can be observed in the parietal and temporal lobes of the brain. 4 Hz to 7 Hz is the normal frequency range of the theta waves[6].

2.1.4. Delta Waves (δ)

Delta waves have a frequency range of 0.5 Hz to 3.5 Hz and an amplitude of 20 to 200 μV[6]. Delta waves are dominant waves in an EEG spectrum during sleep[6].

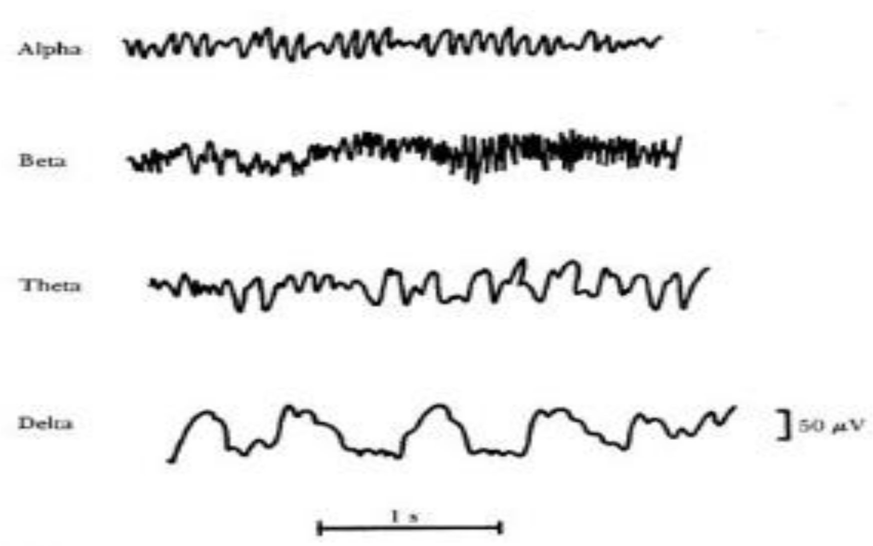


Figure 5: Various waves of normal EEG signal[1]

2.2. Methods to Record EEG

The EEG recording methods can be divided into two broad categories such as (a) Invasive Method of EEG recording and (b) Non-invasive method of EEG recording.

2.2.1. Invasive EEG Recordings

Invasive EEG recording is achieved with the use of either of two different types of electrodes the sub-dural electrodes which are mounted in the surface of the brain or depth electrodes which are penetrated into the brain to measure electrical activity from deep or superficial brain structures.

2.2.2. Non-Invasive EEG Recordings

The non-invasive method of EEG recording is widely used in the applications where the patient under observation is being tested for various brain disorders related to sleep, behavior or trauma to the head.

[1] Figure 5 reused with permission from publisher (Refer Appendix C).

This method involves the use of surface electrodes which are placed on the surface of the patient's scalp. The non-invasive method can be useful when it is necessary that the patient should be active during the entire EEG test. Even though this method does not provide details about deeply located brain structures, a non-invasive method is capable of presenting required data for various applications such as Brain-Computer Interfacing (BCI) and real-time continuous EEG monitoring

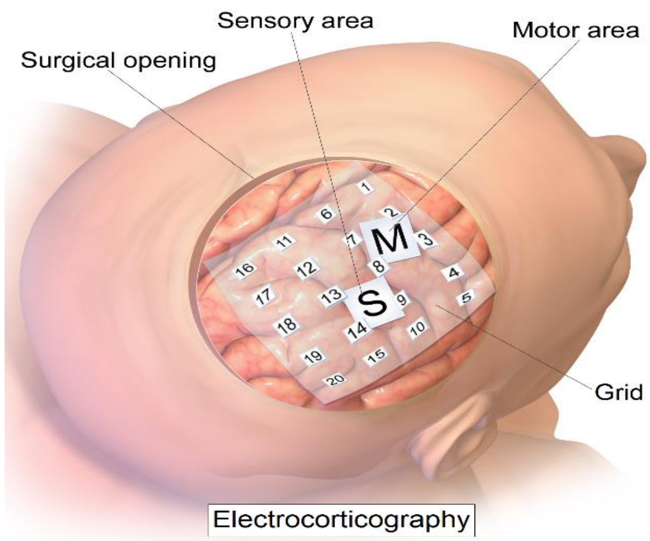


Figure 6: Invasive EEG recording[2]

The non-invasive method of EEG recording is widely used in the applications where the patient under observation is being tested for various brain disorders related to sleep, behavior or trauma to the head. This method involves the use of surface electrodes which are placed on the surface of the patient's scalp. The non-invasive method can be useful when it is necessary that the patient should be active during the entire EEG test. Even though this method does not provide details about deeply located brain structures, a non-invasive method is capable of presenting

[2] Figure 6 reused with permission from publisher (Refer Appendix C)

required data for various applications such as Brain-Computer Interfacing (BCI) and real-time continuous EEG monitoring. The non-invasive EEG recording is carried out using one of the two different electrodes configurations (i) Monopolar electrodes configuration and (ii) Bipolar electrodes configuration. The following figure shows these configurations. The proposed system uses the bipolar configuration of electrode placement.

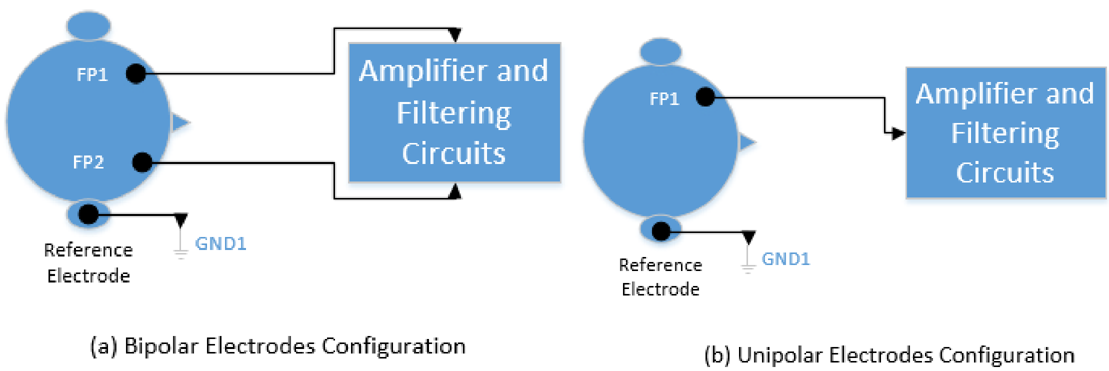


Figure 7: Electrodes configurations for non-invasive EEG measurement

2.3. Application of an EEG in mTBI Detection

Research and studies on mTBI over the year show that the EEG signals can be used to assess the severity and nature of an mTBI. M West et al., conducted research on rats to test the effects of an experimental concussion on EEG signals. [8] In these experiments, the researchers found out that the EEG of those rats who sustained first stage concussion demonstrated considerable decrease in alpha, beta and theta waves (25%, 37% & and 10% respectively) and increased in delta wave amplitude by 15%. On the other hand, the EEG of rats with second-order concussions demonstrated a decrease in all four waveforms by 56%, 49%, 34%, and 31%. This data is represented in table 3.

Table 3: Effects of concussion on EEG components[3]

Concussion Stage	Brain Waves	% Change	Effect
Stage 1-2	alpha	25	Decrease
	beta	37	Decrease
	theta	10	Decrease
	delta	**15**	**Increase**
Stage 3-4	alpha	56	Decrease
	beta	49	Decrease
	theta	34	Decrease
	delta	31	Decrease

SPECTRAL EEG CHANGES IN CONCUSSED RATS

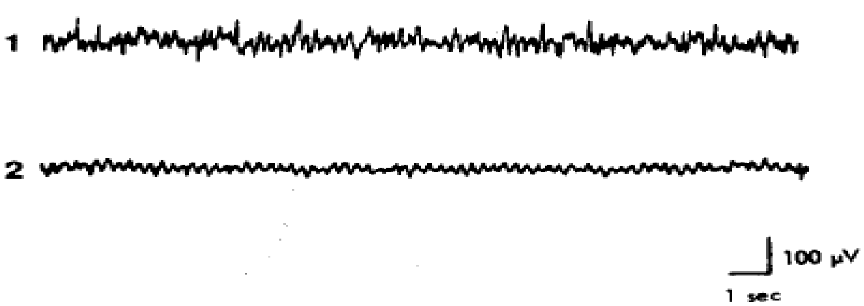


Fig. 1. EEG record before and after concussion. 1: control pre-concussion record from the right sensori-motor cortex. 2: record taken 4.8 min post concussion. There is marked depression of the alpha and beta frequencies, with the appearance of theta rhythm (6 mm/sec). Calibration is in lower right corner.

Figure 8: Changes in an EEG signal immediately following the concussion[4]

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[3] Table 3 is based on data from paper “Spectral analysis of the electroencephalographic response to experimental concussion in the rat"

[4] The Image 8 has been previously published in “Spectral analysis of the electroencephalographic response to experimental concussion in the rat"; M West, D Parkinson, V Havlicek, Electroencephalography and Clinical Neurophysiology, Volume 53, Issue 2, 1982 and is reused with permission from Elsevier Publication.

Apart from these tests carried out on rats to monitor the changes in EEG after the concussion, R. S. Dow et al., and L. E. Larsson et al., carried out two separate studies on human subjects to examine the effects of traumatic brain injuries on an EEG within few minutes of injury occurrences. In the first study carried out by R. S. Dow et al., EEG signals of shipyard workers were recorded within 10-15 minutes of brain injury[2]. The second study was focused on boxing players in order to record the EEG activity as soon after injury as possible[2]. Table 4 summarizes the findings of these two studies.

Table 4: Summary of previous studies of EEG immediately after mTBI

Study	**Outcomes**
Dow study in the shipyard – 10 to 15 minutes after injury	Diffused slowing of EEG (mainly in subject tested soonest after injury)
Larsson Study on Boxers – 15 to 30 minutes after injury	Reduced amplitudes of EEG waves and irregular theta activities

2.4. Summary

The second chapter introduces the electrophysiological fundamentals of an electroencephalogram (EEG) signal, and its amplitude and frequency characteristics. Along with introducing the EEG signal, the various methods to record the EEG and have also been discussed in this chapter. This chapter also presents the EEG data obtained in previous studied carried out on rats as well as human subjects. These tests were carried out to monitor the effects on normal characteristics of an EEG signal. These studies lay out a foundation for the proposed system.

CHAPTER 3:

EEG ACQUISITION SYSTEM DESIGN

Why the EEG acquisition system embedded into a sports helmet? It is clearly evident that there is a remarkably low number of research and development efforts to study the effects of traumatic brain injuries on EEG signals of a human subject. This limitation creates a hindrance in diagnosing traumatic brain injuries and their treatments. This chapter discusses the design of the proposed system which is the first step in the design of a prototype system that will be able to detect a TBI in real-time based on EEG signals measured from a human subject.

3.1. Block Diagram

The diagram below represents the functional blocks implemented in the system design, which contains a single channel electrodes placement, source follower, filter stages and a wireless trans-receiver module. Each section is described in details in the following sections of this chapter.

3.2. Block Diagram Description

3.2.1. Bio-Potential Electrodes

Bio-potential electrodes provide the primary measure to link the body signals and the measurement electronics system. Transducing the bio-signal into the electronic signal is the principal role of the biopotential electrodes. In the body, the bio-potentials are generated due to the ionic movements due to the biochemical activities. On the other hand, in measurement circuits, the current flows in the form of electrons. Thus, the electrodes convert the ionic movements into electrons movements.

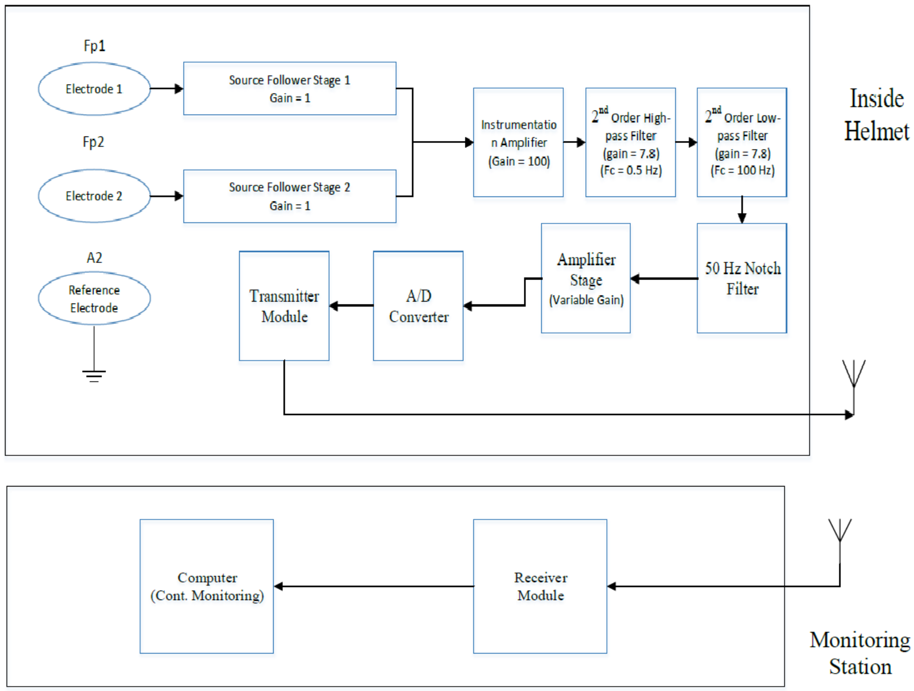
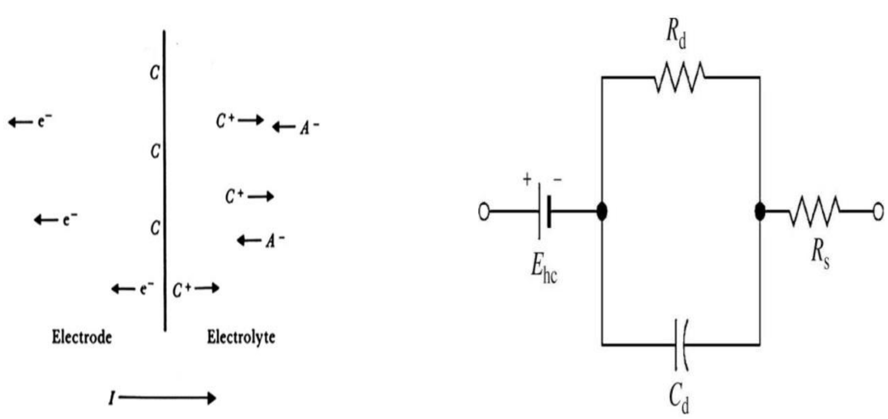


Figure 9: EEG system block diagram



(a) (b)

Figure 10: (a) Electrode-electrolyte interaction. (b) Equivalent circuit of bio-potential electrodes.[5]

[5] Figures 10(a) and 10(b) are reused in this thesis with permission from Wiley Publications. Refer Appendix C.

In the proposed system, the electrodes used are of non-invasive, skin-surface mount snap on electrodes. These electrodes are equipped with Silver-Silver chloride gel (Ag-AgCl gel). The application of Ag-AgCl gel not only acts as a transducer for bio-potentials but also reduces noise in the signal. As described in figure 4 and figure 7, the proposed system uses the single channel, bipolar montage configuration for the EEG electrodes placement. In this configuration, the two bio-potential recording electrodes are placed on positions Fp_1 and Fp_2 respectively, and the reference electrode is placed on the ear lobe. This single channel configuration has been chosen for the proposed system to avoid improper contact with the skin as well as to reduce the discomfort that may be caused to the user.

3.2.2. Source Follower Stage

The source follower stage is the first stage acting as a link between the bio-signal measured by the electrodes and the electronic circuit which is responsible for the amplification and the filtering out the noise from required bio-signals. As the name implies, the source follower amplifier generates an output exactly similar to the input, which means the output of a buffer amplifier is in phase with the input having the same amplitude. These amplifiers act as a buffer stage between different impedance level circuits. Thus, the buffer amplifier can be used to reduce the loading of the next stage[6].

3.2.3. Instrumentation Amplifier

This is the second stage in the EEG circuit design, which consists of a special type of an operational amplifier (op-amp) called "instrumentation amplifier." In the process of measuring bio-potentials, the op-amp must have qualities such as precise control over gain, ability to measure considerably-low level signals and high common mode rejection ratio (CMRR), and a high slew rate[6]. Instrumentation amplifier offers three advantages which play an essential role in the process of bio-potential circuit design, which are high CMRR, high gain, and high input impedance. The CMRR of an amplifier is the ratio of the differential gain and the common mode gain. In other words, it is an ability of an amplifier to reject the common mode input present at its input pins. As the proposed system measures the EEG with bipolar electrodes configuration (refer figure 7(a)), the possibility of generation of common mode signal in addition with the differential signal cannot be discarded entirely. Thus, from the definition of CMRR, we can clearly say that the instrumentation amplifier with the higher CMRR is better suited for the proposed application.

$$CMRR = \frac{A_D}{A_{cm}}$$

Equation 1: Common Mode Rejection Ratio[6]

where A_D is differential mode gain, and A_{cm} is common mode gain.

The primary reason for using the INA129 instrumentation amplifier in the design is that it provides high common mode rejection ratio of 120dB minimum. Another essential characteristic of an op-amp is the differential gain. The INA129 offers gain adjustment with the use of just one resistor, setting the gain from 1 to 10000. The value of the gain setting resistor can be calculated with the following equation:

$$G = 1 + \frac{49.4\ K\Omega}{R_G}$$

Equation 2: INA129 Gain Calculation[7]

where G is differential gain and R_G is gain setting resistor.

[6] Equation is previously published in Gayakwad, R. A. (2000). Op-amps and linear integrated circuits (4th ed.). Upper Saddle River, NJ: Pearson Education

[7] The gain setting resistor value calculation equation is from the datasheet of INA129

Thus, it becomes significantly convenient to change the gain as per the need of an application. Figure 11 is the schematic representation of the INA129 instrumentation amplifier used in circuit design.

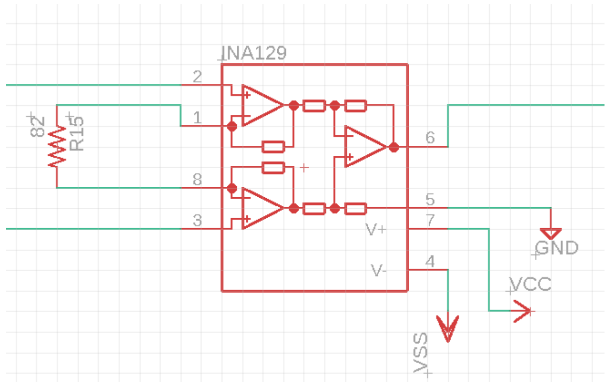


Figure 11: Instrumentation amplifier design

3.2.4. Filter Stages

As discussed in previous chapters, the EEG signal lies in between the frequency range 0.5 Hz to 100 Hz[6]. In order to remove the unwanted signals from the signal of interest, such as 50 Hz power-line noise, the system design includes the three different types of active filters namely, high-pass filter, low-pass filter, and a notch filter. These filter designs are discussed in details in the following sections. The high-pass filter and the low-pass filters are implemented using the Butterworth-Filter design, considering its flat response in the pass-band and the simplicity of its design.

3.2.4.1. Second Order Butterworth Low Pass Filter

The low pass filter used in the system design is a second order Butterworth-Filter, which has a roll-off frequency of -40 dB/decade. Thus, the output gain of the filter decreases at the rate of 40 dB as input frequency is increased by the amount of 10 after the cutoff frequency. [7] The low pass filter is designed for the cutoff frequency of 100Hz and the gain of 1.58. The following figure (Figure 12) shows the SPICE simulation of the filter circuit.

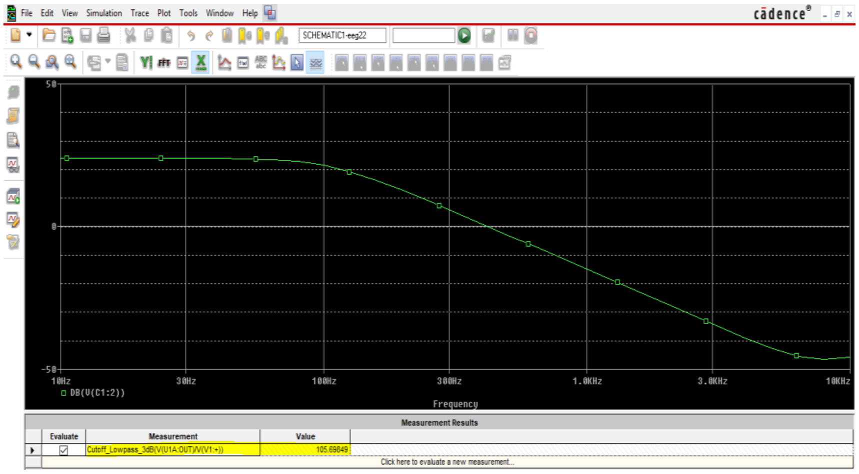


Figure 12: Second order low pass filter response

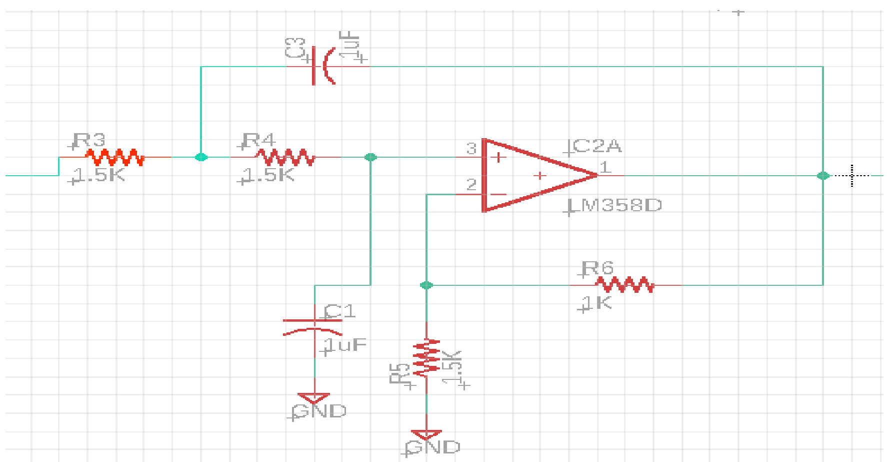


Figure 13: Second order low pass filter design

3.2.4.2. Second Order Butterworth High Pass Filter

Similar to the design of low pass filter, the high pass filter also has the roll-off frequency of 40 dB/decade in this design, with the interchanged positions of capacitors and resistors. This filter is designed for the cut-off frequency of 0.5Hz. This implies that the gain of this filter at input frequency 0.5 Hz is -3dB less than the gain at the pass-band frequency. By combining this filter with a low-pass filter, the resulting circuit forms the bandpass filter and has a bandwidth of 99.5 Hz with cut-off frequencies at 0.5Hz and 100 Hz.

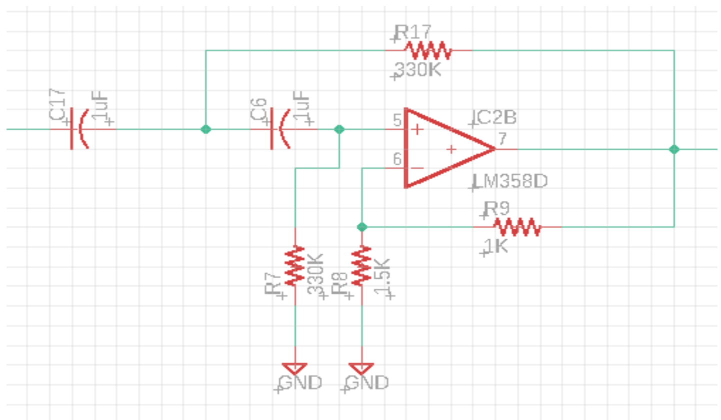


Figure 14: Second order high pass filter design

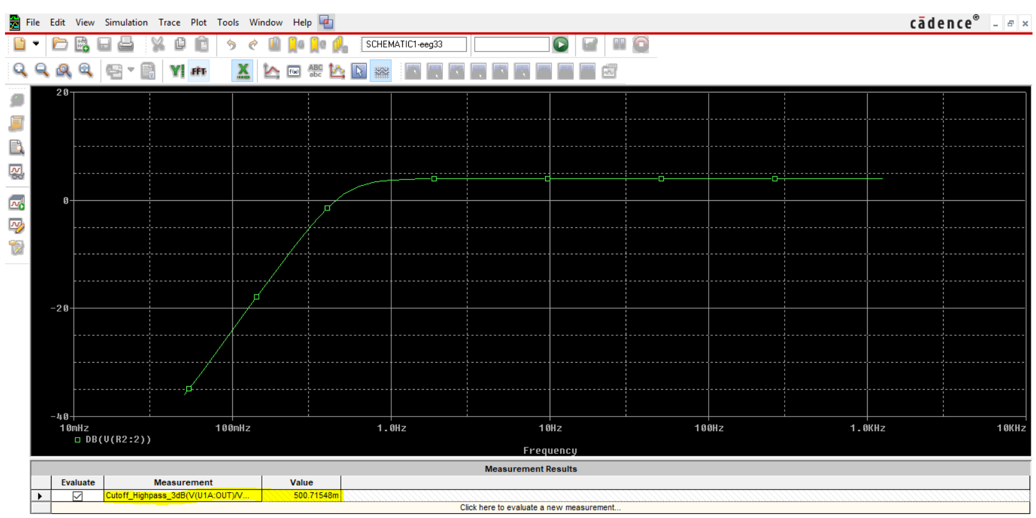
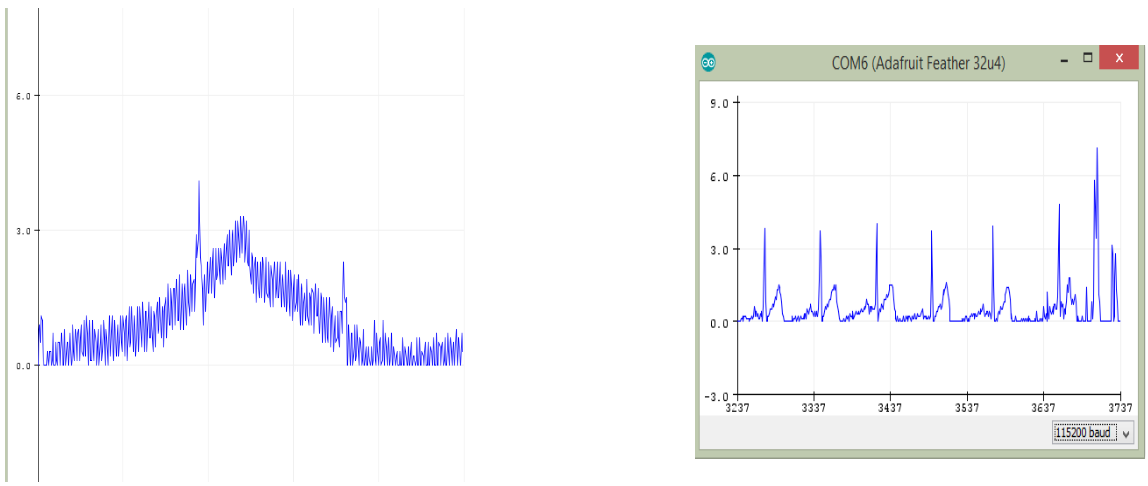


Figure 15: Second order high pass filter response

3.2.4.3. Notch Filter

As the name suggests, the notch filter blocks the specified band of input frequencies. The frequency response of this filter resembles a notch. The notch filter is designed to block the power line noise i.e. 60 Hz hum caused by the power line. Even though the proposed system is battery powered in the received signals, we observed the presence of humming noise. Figure 16(a) is the ECG signal received without the use of the notch filter and figure 16(b) is the result after the use of the designed notch filter. The ECG signal is used here to illustrate the benefit of the notch filter.

The notch filter implemented in this design has a first order frequency response with the gain of 1.85. As the first order filter does not have a sharp roll-off frequency, the notch frequency, in other words, the stop band of the designed filter is comparatively larger (refer figure 17 and figure 18).



(a) (b)

Figure 16: (a)Received ECG signal prior to implementing notch filter. (b) Obtained ECG signal after implementing a notch filter

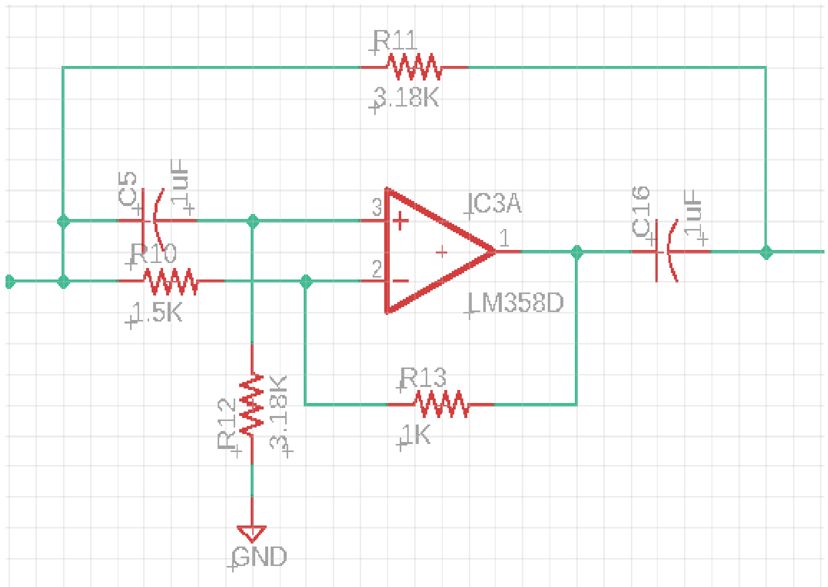


Figure 17: 60Hz notch filter

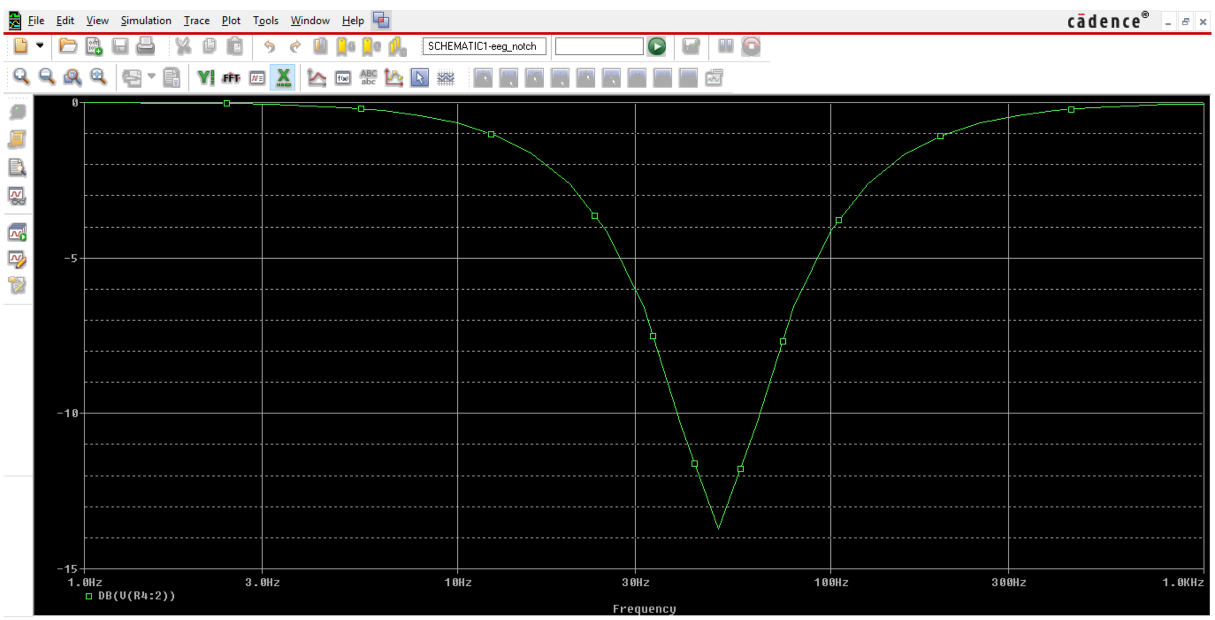


Figure 18: 60Hz notch filter response

3.2.5. Post Amplifier

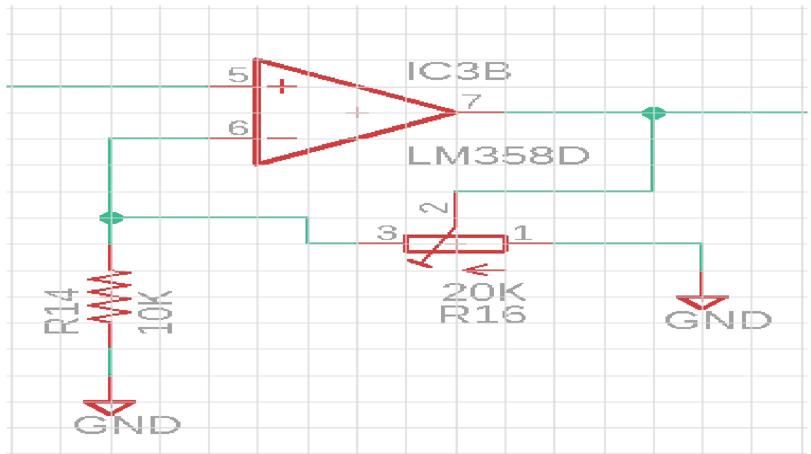


Figure 19: Non-inverting post amplifier with variable gain

The non-inverting post amplifier is the last stage of the analog bio-signal processing unit of the system. The post-amplifier stage receives the bio-signal acquired by the electrodes, amplified, and filtered by various stages. The main reason to use the post-amplifier stage in this design is to allow the user to adjust the gain of the output analog signal as per the requirement and capability of the A/D converter. The bio-signal acquired by the electrodes is amplified by the fixed total gain of 2025 (gain calculations can be found in appendix 2) before it is fed to the post-amplifier. The post-amplifier has the maximum gain of 3. Thus, the biosignal after the post amplifier is amplified by the gain of 7372, assuming the post amplifier is at its maximum gain settings.

3.2.6. Wireless Transmitter Module

The main function of this system is to transmit the processed EEG data of a football player and transmit it to the monitoring station where the sports physicians can monitor the data for any possibilities of concussion or other types of brain injuries. To achieve this without interfering or ceasing player’s normal activities, it was necessary to have a system that is able to transmit the data with a wireless communication protocol. The Feather 32u4 RFM69 Packet Radio by the Adafruit which is a radio trans-receiver module has been used in the system to achieve wireless transmission of the processed EEG data. As the proposed system is designed to work from within the player’s helmet, it was necessary to save the space with the use of as small components as possible. The Feather module has a wireless trans-receiver and a microcontroller on the same PCB, which made it an ideal choice of trans-receiver device to be used in the proposed system.

3.2.6.1. Feather RFM69 Overview

- The Feather RFM69 module has an onboard microcontroller Atmega32u4, which is the heart of the wireless transmitter system. The A/D converter of Atmega32u4 is used to convert the analog EEG signal into digital signal.
- Wireless module - The RFM69HCW radio uses the Industrial, Scientific, and Medical (ISM) radio band as the radio frequency. This module uses 900 MHz as a radio frequency which license-free ISM for the United States. [10] The Atmega32u4 communicates with the RFM69HCW using SPI communication protocol. [10]

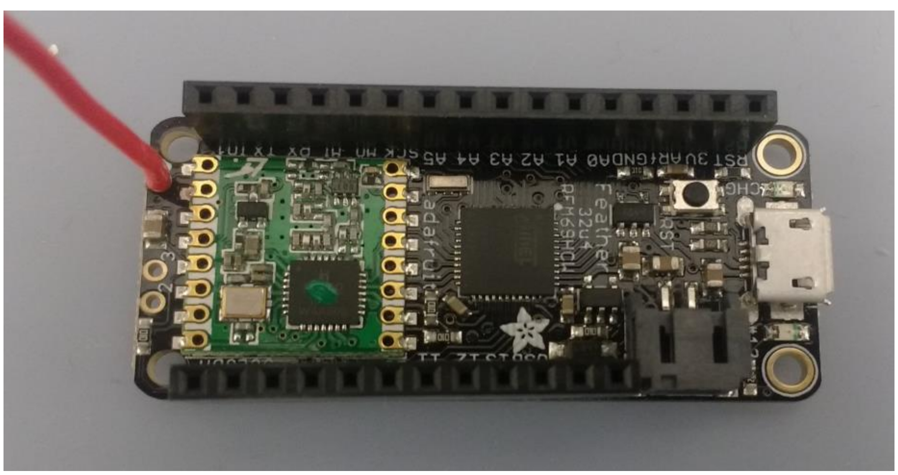


Figure 20: RFM69 Trans-receiver module

- In the proposed system the required range of data transmission is up to 100m in sight-of- line. This range is estimated based upon the area of an American football field which is 94.44m x 48.8m. As Feather RFM69 module offers a 500 m range of communication in line-of-sight [10], this module was selected as the wireless trans-receiver device.

3.2.7. Receiver Module

The receiver module is the Feather RFM69 module, similar to the one used in the transmitter. This module receives the EEG data and is then given to the 32u4 microcontroller. The microcontroller then scales the EEG data from the 0 to 1024 steps to 0 to 5 V.

3.3. Graphical User Interface (GUI) Design

Laboratory Virtual Instrument Engineering Workbench (LabVIEW) which is a graphical programming language platform for the development of graphical user interface and data acquisition, is used to monitor the EEG waveforms received by the monitoring station. The LabVIEW programming environment consists of two different parts namely block diagram and a front panel. The block diagram consists of a series of blocks which defines the flow of data from input to the output creating a well-functioning program which is termed as a virtual instrument (VI). On the other hand, the front panel forms a graphical user interface, containing indicators, controls, and constants. The following figure shows the design of the block diagram of the EEG data acquisition system. Virtual Interface Software Architecture (VISA) interface is the first stage in the block diagram. The VISA provides a programmable interface between a serial device and the LabVIEW. VISA has three inputs which are baud rate, number of bits and input serial port. These inputs are configured as a control and are displayed on the front panel for the user interface. The next step is VISA read which reads the specified numbers of the data byte and returns it to the read buffer. The output of the read buffer is then scanned to check the presence of a data string. This data string is then extracted and displayed as a waveform.

The following figure represents the design of front panel which consists of a waveform display (indicator), baud rate input (control), serial port input (control), number of data bits (control). This whole process is repeated continuously with the use of while loop implemented in the block diagram.

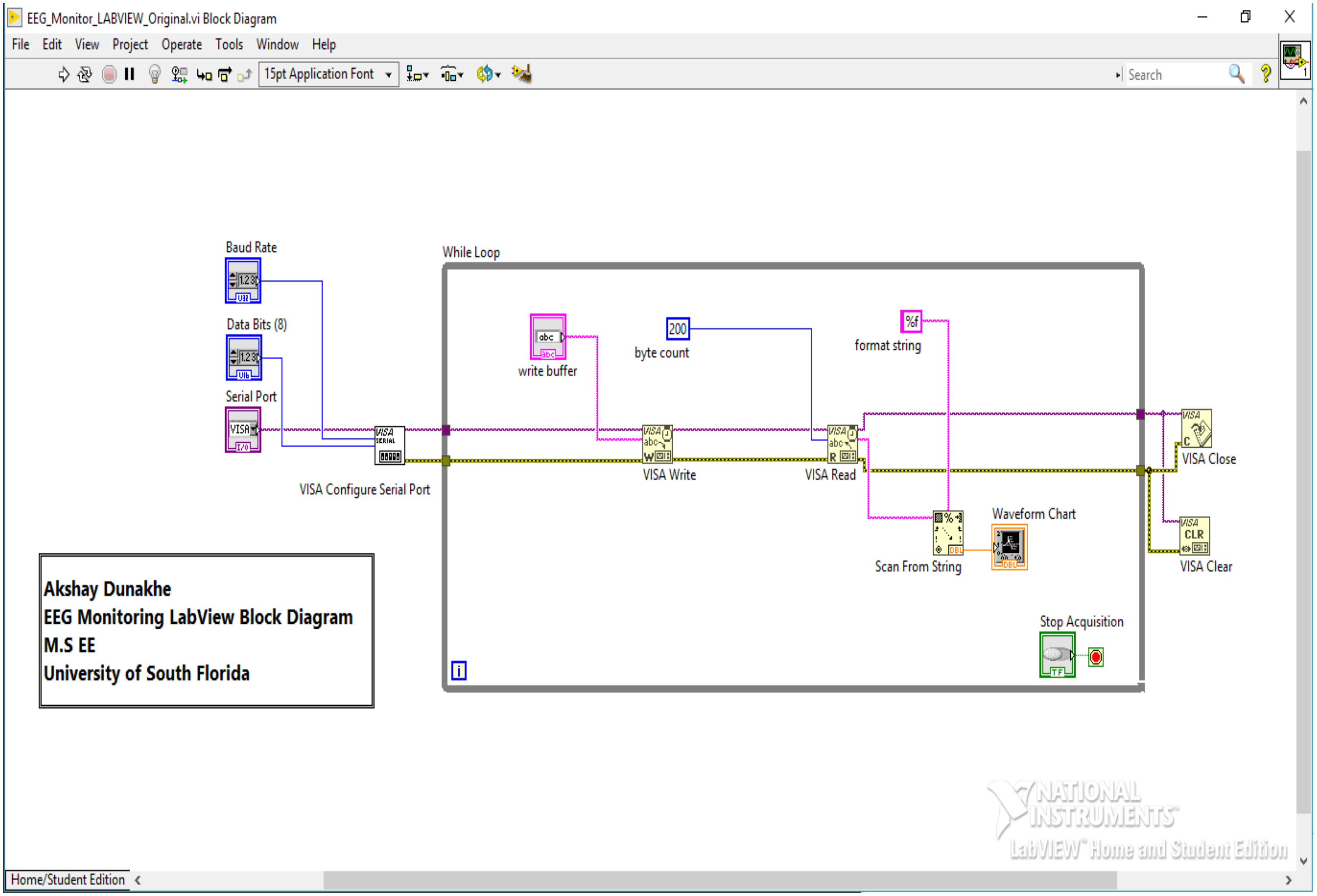


Figure 21: Block diagram of EEG data acquisition system

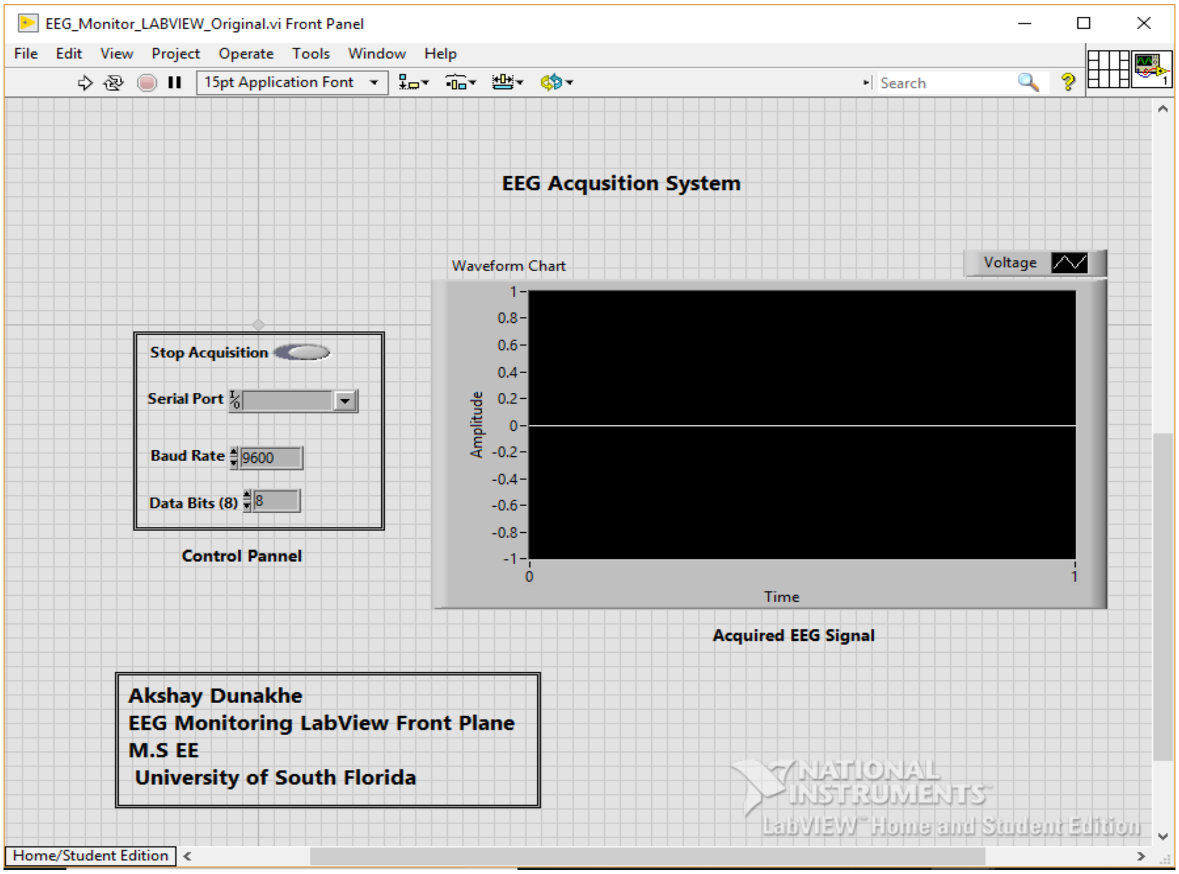


Figure 22: Front panel of EEG data acquisition system

3.4. System Specifications

The recommended specifications of an EEG system are mentioned in the following table; these specifications can be considered as standards in order to acquire a reliable EEG signal. Although Saurabh R. Sinha et al. states that it is necessary to have at least 16 channels of EEG recording to obtain reliable EEG data [11], the scope of the proposed system involves the use of only one EEG recording channel (Fp1 and Fp2). This configuration serves two purposes which are firm contact of electrodes with forehead skin and space optimization inside a helmet. Majority of other specifications are satisfied during the system design process.

Table 5: Technical specifications of developed system

Sr. No.	Parameter	Values	
		Required	**Actual**
1	Electrodes	Ag-AgCl or Gold disk electrodes	Ag-AgCl electrodes
2	Number of Channels	25 - 32	1
3	Input Impedance	10Mohm	10Mohm
4	CMRR	>100	112
5	Cutoff frequency	High-pass 0.5 Hz Low-pass 100 Hz Notch Filter 60 Hz	High-pass 0.5 Hz Low-pass 100 Hz Notch Filter 60 Hz
6	Electrode Impedance	<5Mohm	Approx. 1Mohm
7	ADC Resolution	12 bits	10 bits
8	Supply Voltage (EEG Circuit)	-	9V
9	Supply Voltage (Radio Trans-receiver)	-	3.3V
10	Wireless Connectivity Range	At least 110 m	500m In-Line of Sight

3.5. Summary

This chapter outlined the system design process of the proposed work. I order to remove unwanted noise and provide adequate amplification of a bio-signal being monitored undergoes various filter and amplifier stages. These stages are bio-amplifier (instrumentation amplifier), low-pass filter and high-pass filter, notch filter and post amplifier. The initial prototype design was implemented on a breadboard. As the goal of this work was to develop a system that can be embedded inside an American football helmet, we designed two variants of PCB. The first iteration of the PCB is traditional (rigid) PCB. The second PCB is flexible PCB designed to achieve goals such as space optimization, ergonomic design and protection to the circuit from impacts. During the design process of flexible PCB, we encountered various problems due to the structural limitations. Thus, the flexible PCB requires more development in order to function more efficiently. The GUI designed which continuously monitor the EEG works as per the design requirements. However, there are some known issues which need to be addressed in the future.

CHAPTER 4:

RESULTS

This section summarizes the overall performance of the EEG monitoring system developed. The system design is evaluated in three different ways. Firstly, the circuit was tested to monitor the ECG signal. As an ECG signal has a characteristic profile and comparatively large amplitude than the EEG signal, this step proves to be a crucial validating step. In the next step, the EEG signal was monitored on a digital storage oscilloscope (DSO). This step not only allowed the examination of characteristics of processed EEG signal such as amplitude and frequency but also helped in identifying the different types of EEG waves. In the final step, the processed EEG signal was monitored in GUI developed in LabVIEW. Following subsections discuss the results of each evaluation step.

4.1. Circuit-Test for ECG Signal

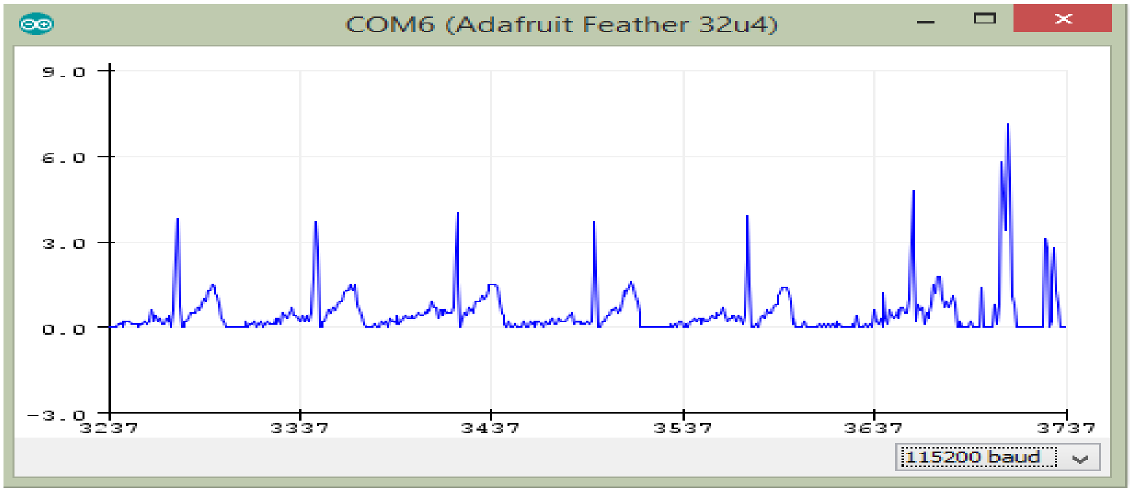


Figure 23: ECG signal obtained with the designed system

The above image displays the ECG signal obtained with the designed circuit. The obtained signal does not show any displacement of the signal from the baseline. Also, the signal does not have any humming noise. The last portion of signals shows distortion which is the result of movement.

4.2. EEG Signal Monitored Using DSO

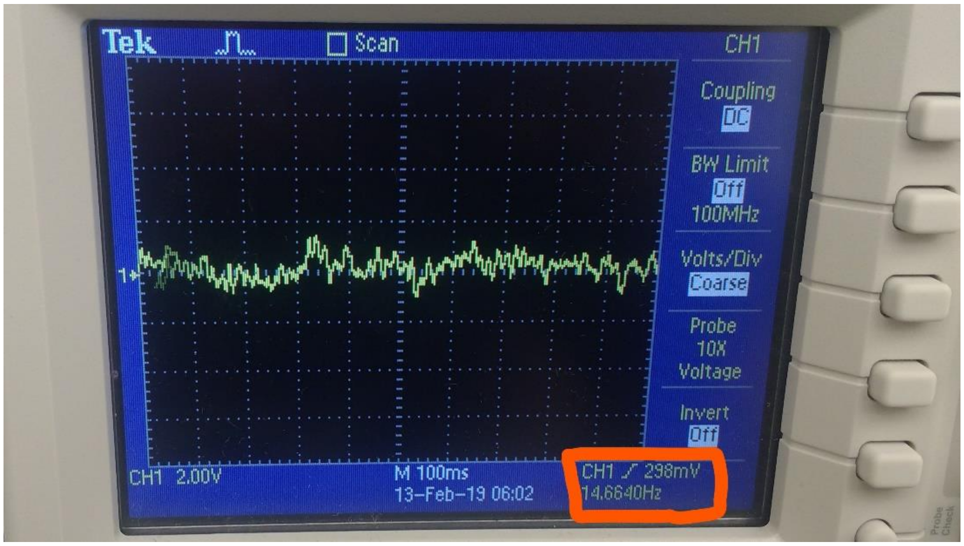


Figure 24: EEG signal monitored on DSO

Above image displays the EEG signal obtained from the analog signal processing circuit and monitored on DSO. Similar to the results of the ECG test, the EEG signal also does not exhibit any base-line shift or a presence of humming noise. The obtained EEG signal can be identified as beta waves depending on the morphology of waveform and the frequency of the signal which is 14.66 Hz (frequency of normal beta waves – 14 Hz to 30 Hz (section 2.1.2)).

4.3. EEG Signal Monitored on LabVIEW GUI

This subsection shows the processed EEG signal received with the wireless communication module at the monitoring station and then displayed on the LabVIEW GUI.

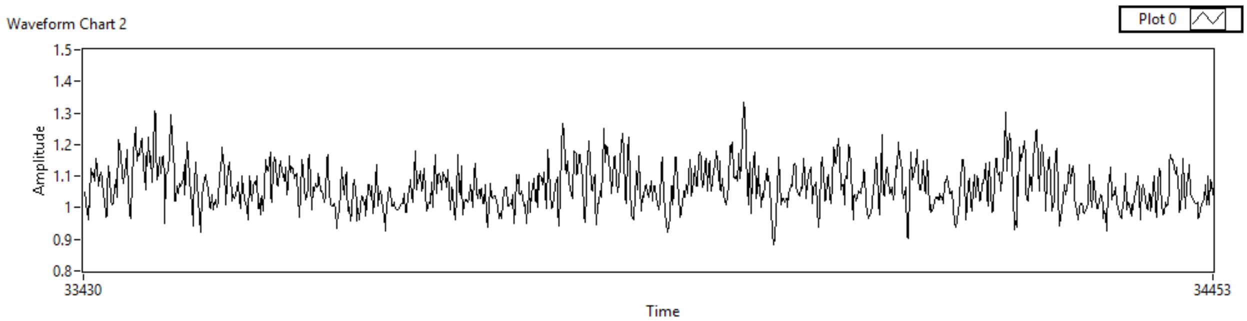


Figure 25: Final EEG signal as monitored in LabVIEW GUI

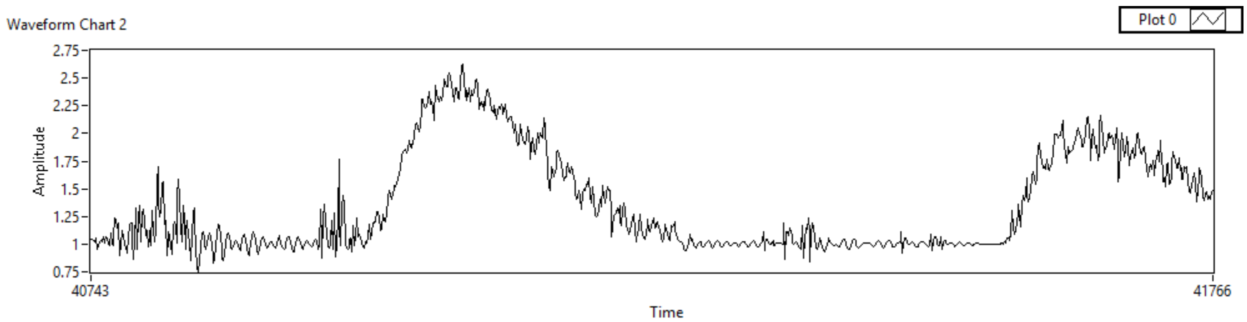


Figure 26: Final EEG signal with distortion due to eye movement as monitored in LabVIEW GUI

CHAPTER 5:

CONCLUSION AND FUTURE WORK

5.1. Conclusion

The Wireless EEG system for monitoring of real-time m-TBI in sports developed during this thesis work, especially in football players, can be a promising advancement in the field of injury detection and treatment. This thesis discussed the design, development, and testing of the EEG monitoring system. At this level, we were able to develop and test the EEG signal monitoring system prototype successfully.

The designed system generated satisfactory results based on measured and simulated data. The system could successfully remove various types of noise from the signal such as power-line noise and signal base-line shift. In addition to this, the designed system also provided a variable gain option. This feature enables users to choose gain settings and display the signal according to their requirements. The wireless communication feature of the system performed satisfactorily. The LabVIEW GUI displayed the EEG signal received over the wireless communication protocol with auto-scaled graphs.

The current system design used gel electrodes to sense the EEG signals. In the future, these electrodes can be replaced with dry electrodes for improved performance. Integration of the proposed system into the helmet with more advanced technology, such as flexible PCB and metal deposited electrodes, can open numerous paths for development of new brain injury detection devices.

5.2. Future Work

Even if the thesis work presented is still in the prototype design stage and does not detect the concussions in real-time, the proposed system directs us towards the development of an exciting system. The proposed system requires further development in a few areas, but not limited to, full system integration into a football helmet, redesign of bio-potential electrodes, redesign of the traditional rigid (i.e. non-flexible) PCB and redesign of the EEG acquisition GUI. This chapter lists out some of the areas where we believe that the proposed system can be improved.

5.2.1. Full System Integration

The goal of the entire project was to develop an EEG system to be integrated into a football helmet. While we designed a portable system that can record an EEG signal, we could not alter or damage the standardized helmet design. Thus, during the entire course of the system design phases, we identified a few of the places inside the helmet where the proposed system can be placed without damaging or altering the structure. These places are presented in the pictures at the end of this chapter. Image 26(a) represents the available spaces between the protective cushioning and the outer shell of the football helmet. The image 26(b) represents the integration of the first iteration of system PCB, wireless transmitter module and three bio-potential electrodes. To improve space utilization, we are currently working on the development of flexible PCB (refer to images at the end of the chapter).

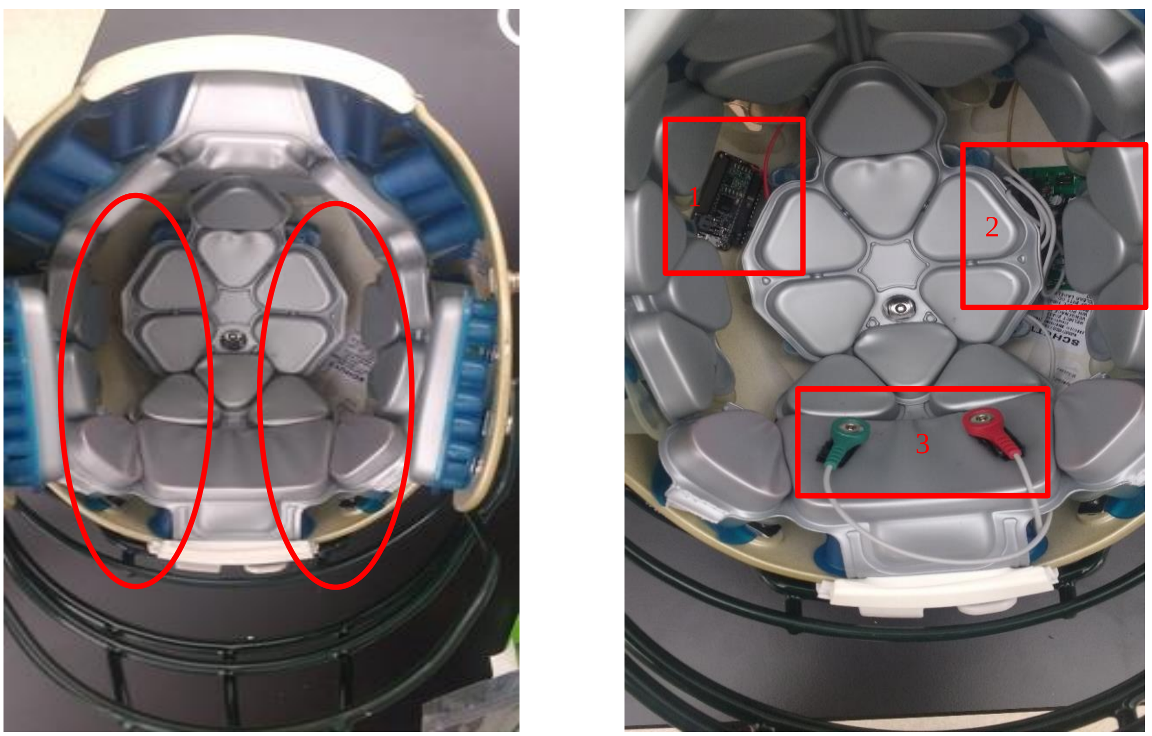
5.2.2. Redesign of Bio-Potential Electrodes

Throughout system design, it was observed that traditional electrodes being used in the current system tend to cause discomfort to the helmet wearer. Thus, it is important to redesign the electrodes such that they will not cause any discomfort to the user while keeping the signal quality equal to that of traditional electrodes.

5.2.3. Redesign of EEG Acquisition GUI

In the current system design, the EEG signal is monitored using a LabVIEW graphical user interface (GUI). Even though this GUI allows the user to control and monitor signal acquisition using various functions available in LabVIEW, there are known limitations of the current GUI. This section summarizes these known limitations and future steps that should be taken to improve the user experience related to the system GUI.

- It is a known fact that the power spectrum of an EEG signal has equal importance as a raw EEG signal, in clinical analysis. The current GUI does not display the power spectrum. In the future, the GUI can be redesigned in order to display the power spectrum of an EEG signal.
- In the future, the GUI can be redesigned to function more like an oscilloscope, allowing in-depth analysis of a received EEG signal.



(a) (b)

Figure 27: (a) Available spaces inside the American Football helmet. (b) System integration with first iteration of PCB

In figure 27(a), the encircled areas represent the available space between outer shell of a football helmet and protective pads. Figure 27(b) represents the system integration with first iteration of PCB. The legends for this figure are as follows:

1. Wireless Transmitter module.
2. System PCB.
3. Bio-potential electrodes placed at locations relative to Fp1 and Fp2 locations.

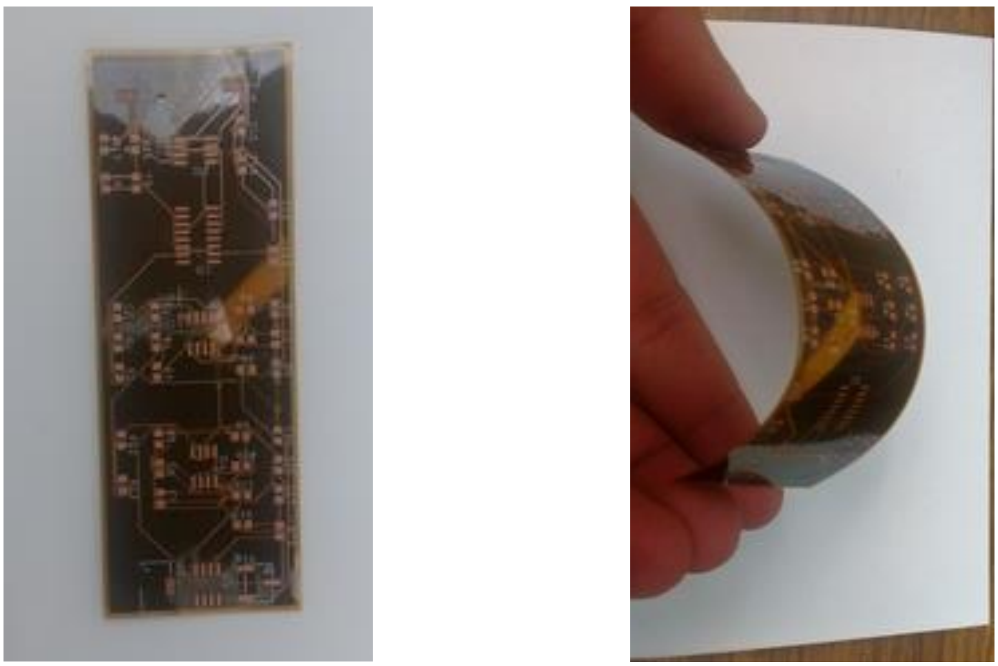


Figure 28: Flexible PCB design

REFERENCES

[1] Centers for Disease Control and Prevention. (n.d.). Retrieved from https://www.cdc.gov/traumaticbraininjury/index.html

[2] Nuwer, M. R., Hovda, D. A., Schrader, L. M., & Vespa, P. M. (2005). Routine and quantitative EEG in mild traumatic brain injury. Clinical Neurophysiology, 116(9), 2001-2025.

[3] Neurosurgical Conditions and Treatments – Concussion. Retrieved from https://www.aans.org/Patients/Neurosurgical-Conditions-and-Treatments/Concussion

[4] Straus, L. B., JD. (n.d.). Neurocognitive Testing for Concussions Different rules for children, adolescents. Retrieved from https://www.momsteam.com/health-safety/concussion-safety/recognition-evaluation/neuropsychological-testing-for-concussions

[5] Khandpur, R. S. (1994). Handbook of biomedical instrumentation. Tata McGraw-Hill Education.

[6] Webster, J. G. (2009). Medical instrumentation application and design. John Wiley & Sons.

[7] Gayakwad, R. A. (1993). Op-amps and linear integrated circuits. Prentice-Hall, Inc..

[8] Ahmadian, P., Cagnoni, S., & Ascari, L. (2013). How capable is non-invasive EEG data of predicting the next movement? A mini review. Frontiers in human neuroscience, 7, 124.

[9] West, M., Parkinson, D., & Havlicek, V. (1982). Spectral analysis of the electroencephalographic response to experimental concussion in the rat. Electroencephalography and clinical neurophysiology, 53(2), 192-200.

[10] Adafruit Feather 32u4 Radio with RFM69HCW Module. Retrieved from https://learn.adafruit.com/adafruit-feather-32u4-radio-with-rfm69hcw-module.

[11] Sinha, S. R., Sullivan, L. R., Sabau, D., Orta, D. S. J., Dombrowski, K. E., Halford, J. J., ... & Stecker, M. M. (2016). American clinical neurophysiology society guideline 1: minimum technical requirements for performing clinical electroencephalography. The Neurodiagnostic Journal, 56(4), 235-244

[12] Echemendia, R. J., & Julian, L. J. (2001). Mild traumatic brain injury in sports: neuropsychology's contribution to a developing field. Neuropsychology review, 11(2), 69-88.

[13] Sahler, C. S., & Greenwald, B. D. (2012). Traumatic brain injury in sports: a review. Rehabilitation research and practice, 2012.

[14] Weiner, M. F., & Lipton, A. M. (Eds.). (2009). The American Psychiatric Publishing textbook of Alzheimer disease and other dementias. American Psychiatric Pub.

[15] Ianof, J. N., & Anghinah, R. (2017). Traumatic brain injury: An EEG point of view. Dementia & Neuropsychologia, 11(1), 3-5.

[16] Diez, P. F., Mut, V., Laciar, E., & Avila, E. (2010, August). A comparison of monopolar and bipolar EEG recordings for SSVEP detection. In 2010 Annual International Conference of the IEEE Engineering in Medicine and Biology (pp. 5803-5806). IEEE.

[17] Li, P., Meziane, R., Otis, M. J. D., Ezzaidi, H., & Cardou, P. (2014, October). A Smart Safety Helmet using IMU and EEG sensors for worker fatigue detection. In 2014 IEEE International Symposium on Robotic and Sensors Environments (ROSE) Proceedings (pp. 55-60). IEEE.

[18] Von Rosenberg, W., Chanwimalueang, T., Goverdovsky, V., Looney, D., Sharp, D., & Mandic, D. P. (2016). Smart helmet: Wearable multichannel ECG and EEG. IEEE journal of translational engineering in health and medicine, 4.

[19] Veena, D. K., Devaraj, D., Rajasree, P. M., & Oberoi, A. (2014, November). A compact sensor system for concussion mitigation in helmets-A concept prototype. In 2014 International Conference on Contemporary Computing and Informatics (IC3I) (pp. 363-366). IEEE.

[20] Okdeh, M. A., Hage-Diab, A., Haj-Ali, A., & Hussein, B. (2017, October). Concussion detection using a commercially available eye tracker. In 2017 Fourth International Conference on Advances in Biomedical Engineering (ICABME) (pp. 1-4). IEEE.

[21] Balakrishnan, A., & Patapati, S. (2017, October). Automation of traumatic brain injury diagnosis through an IoT-based embedded systems framework. In 2017 IEEE 8th Annual Ubiquitous Computing, Electronics and Mobile Communication Conference (UEMCON) (pp. 645-649). IEEE.

[22] Sjaaheim, H., Albert, B., Setchi, R., Noyvirt, A., & Strisland, F. (2014, October). A portable medical system for the early diagnosis and treatment of traumatic brain injury. In 2014 IEEE International Conference on Systems, Man, and Cybernetics (SMC) (pp. 2529-2534). IEEE.

[23] Cheriyan, A. M., Jarvi, A. O., Kalbarczyk, Z., Gallagher, T. M., Iyer, R. K., & Watkin, K. L. (2009, June). Pervasive embedded systems for detection of traumatic brain injury. In 2009 IEEE International Conference on Multimedia and Expo (pp. 1704-1707). IEEE.

[24] Bhagawati, A. J., & Chutia, R. (2016). Design of single channel portable eeg signal acquisition system for brain computer interface application. International Journal of Biomedical Engineering and Science (IJBES 2016), 3(1), 37-44.

[25] Pu, X. J., Liu, T. J., & Yao, D. Z. (2009). Design of an EEG preamplifier for brain-computer interface. Journal of Electronic Science and Technology, 7(1), 56-60.

[26] Zhang, L., Guo, X. J., Wu, X. P., & Zhou, B. Y. (2013, December). Low-cost circuit design of EEG signal acquisition for the brain-computer interface system. In 2013 6th International Conference on Biomedical Engineering and Informatics (pp. 245-250). IEEE.

[27] Straus, I. B. Neurocognitive Testing for Concussions Different rules for children, adolescents. Retrieved from https://www.momsteam.com/health-safety/concussion-safety/recognition-evaluation/neuropsychological-testing-for-concussions

APPENDIX A:

TBI SYMPTOMS CHECKLIST BY CDC

Concussion Signs and Symptoms

Checklist

Heads Up to Schools: KNOW YOUR CONCUSSION ABCs

Student's Name: ______________ **Student's Grade:** ______ **Date/Time of Injury:** ______

Where and How Injury Occurred: *(Be sure to include cause and force of the hit or blow to the head.)* ______________

Description of Injury: *(Be sure to include information about any loss of consciousness and for how long, memory loss, or seizures following the injury, or previous concussions, if any. See the section on Danger Signs on the back of this form.)* ______________

DIRECTIONS:

Use this checklist to monitor students who come to your office with a head injury. Students should be monitored for a minimum of 30 minutes. Check for signs or symptoms when the student first arrives at your office, fifteen minutes later, and at the end of 30 minutes.

Students who experience *one or more* of the signs or symptoms of concussion after a bump, blow, or jolt to the head should be referred to a health care professional with experience in evaluating for concussion. For those instances when a parent is coming to take the student to a health care professional, observe the student for any new or worsening symptoms right before the student leaves. Send a copy of this checklist with the student for the health care professional to review.

OBSERVED SIGNS	0 MINUTES	15 MINUTES	30 MINUTES	___ MINUTES Just prior to leaving
Appears dazed or stunned				
Is confused about events				
Repeats questions				
Answers questions slowly				
Can't recall events *prior* to the hit, bump, or fall				
Can't recall events *after* the hit, bump, or fall				
Loses consciousness (even briefly)				
Shows behavior or personality changes				
Forgets class schedule or assignments				
PHYSICAL SYMPTOMS				
Headache or "pressure" in head				
Nausea or vomiting				
Balance problems or dizziness				
Fatigue or feeling tired				
Blurry or double vision				
Sensitivity to light				
Sensitivity to noise				
Numbness or tingling				
Does not "feel right"				
COGNITIVE SYMPTOMS				
Difficulty thinking clearly				
Difficulty concentrating				
Difficulty remembering				
Feeling more slowed down				
Feeling sluggish, hazy, foggy, or groggy				
EMOTIONAL SYMPTOMS				
Irritable				
Sad				
More emotional than usual				
Nervous				

To download this checklist in Spanish, please visit: www.cdc.gov/Concussion. Para obtener una copia electrónica de esta lista de síntomas en español, por favor visite: www.cdc.gov/Concussion.

→ More

Figure A1: Symptoms check list by CDC

Danger Signs:

Be alert for symptoms that worsen over time. The student should be seen in an emergency department right away if s/he has:

- ❒ One pupil (the black part in the middle of the eye) larger than the other
- ❒ Drowsiness or cannot be awakened
- ❒ A headache that gets worse and does not go away
- ❒ Weakness, numbness, or decreased coordination
- ❒ Repeated vomiting or nausea
- ❒ Slurred speech
- ❒ Convulsions or seizures
- ❒ Difficulty recognizing people or places
- ❒ Increasing confusion, restlessness, or agitation
- ❒ Unusual behavior
- ❒ Loss of consciousness (even a brief loss of consciousness should be taken seriously)

Additional Information About This Checklist:

This checklist is also useful if a student appears to have sustained a head injury outside of school or on a previous school day. In such cases, be sure to ask the student about possible sleep symptoms. Drowsiness, sleeping more or less than usual, or difficulty falling asleep may indicate a concussion.

To maintain confidentiality and ensure privacy, this checklist is intended only for use by appropriate school professionals, health care professionals, and the student's parent(s) or guardian(s).

For a free tear-off pad with additional copies of this form, or for more information on concussion, visit: www.cdc.gov/Concussion.

Resolution of Injury:

__ Student returned to class

__ Student sent home

__ Student referred to health care professional with experience in evaluating for concussion

SIGNATURE OF SCHOOL PROFESSIONAL COMPLETING THIS FORM: ______________________

TITLE: ______________________

COMMENTS:

For more information on concussion and to order additional materials for school professionals FREE-OF-CHARGE, visit: www.cdc.gov/Concussion.

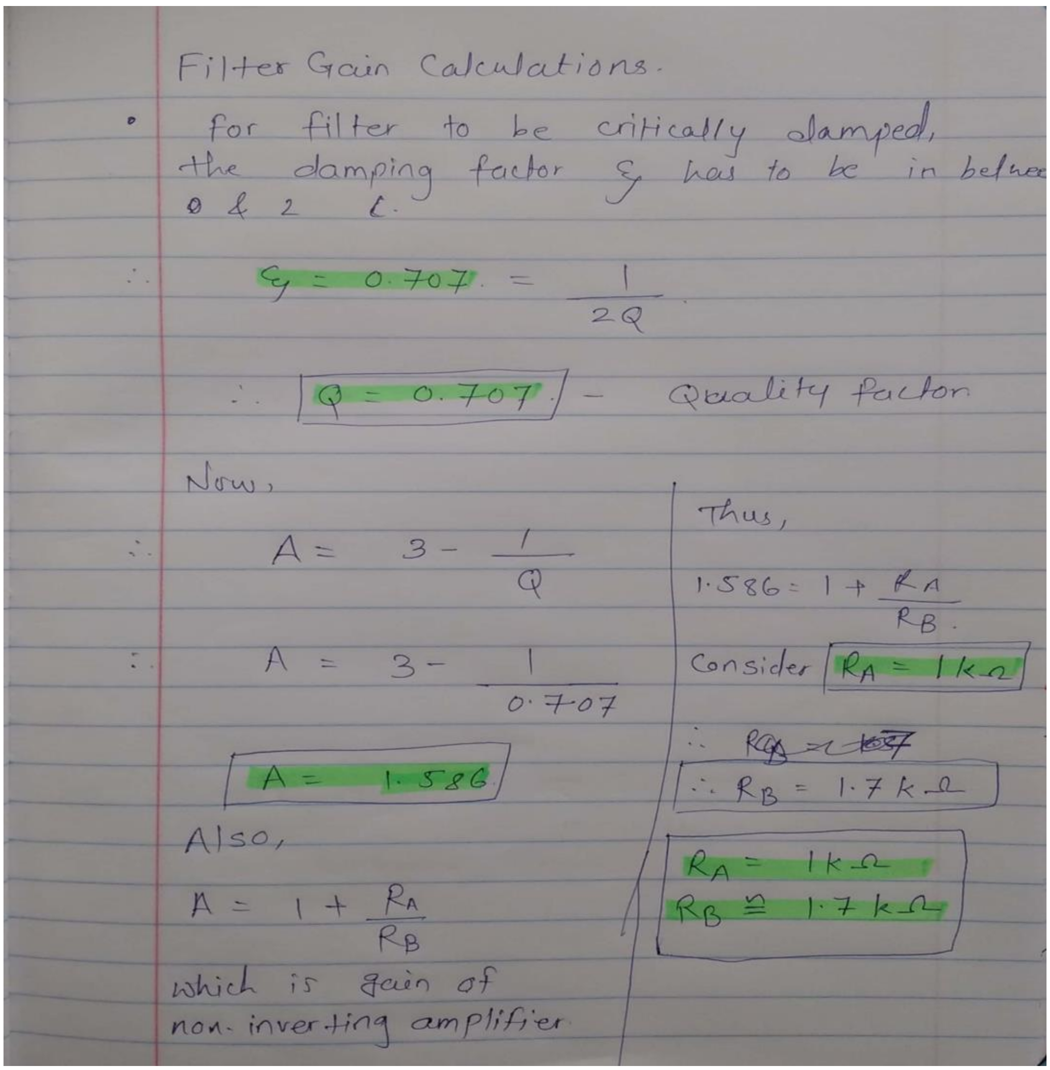
U.S. Department of Health and Human Services
Centers for Disease Control and Prevention

Figure A1 (continued)

APPENDIX B:

CALCULATIONS

B.1. Gain and Quality Factor Calculations for Filters


Filter Gain Calculations.

- For filter to be critically damped, the damping factor ξ has to be in betwee 0 & 2.

∴ ξ = 0.707. = 1 / 2Q

∴ Q = 0.707. – Quality factor

Now,

∴ A = 3 − 1/Q

∴ A = 3 − 1/0.707

A = 1.586

Also,

A = 1 + RA/RB

which is gain of non-inverting amplifier

Thus,

1.586 = 1 + RA/RB.

Consider RA = 1kΩ

∴ RB = 1.7 kΩ

RA = 1kΩ

RB ≅ 1.7 kΩ

Figure B1: Filter gain and Q calculations

B.2. ADC Sampling Frequency Calculations

According to Nyquist theorem, the sampling frequency of an ADC must be at least double than the highest frequency component present in the analog signal. The EEG signal frequency ranges from 0.5 Hz to 100 Hz. Thus, it is essential to have ADC with a sampling rate of 200 Hz or higher. The ADC used in this application provides the sampling frequency of 4807.70 Hz. The sampling frequency is calculated based on the following calculations.

1. Microcontroller Clock Frequency F_{CPU} = 8 Mz
2. Prescalar = 128
3. ADC clock frequency = $\frac{8\ Mz}{128} = 62500$
4. Every conversion requires 13 ADC clock cycles, thus, ADC sampling frequency f_s = 4807.70 Hz

APPENDIX C:

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APPENDIX D:

EEG CIRCUIT PCB DESIGN

D.1. PCB Design (Rigid PCB) – First Iteration

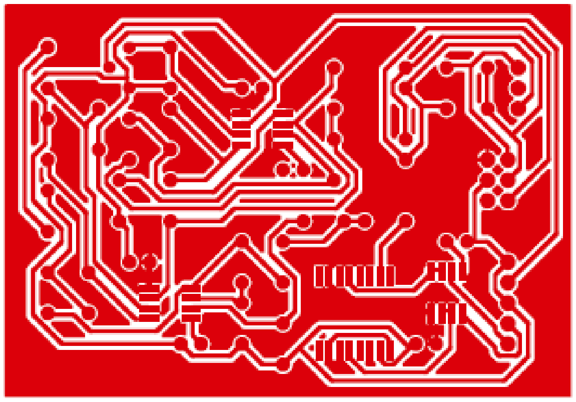

Figure D1: PCB top layer design

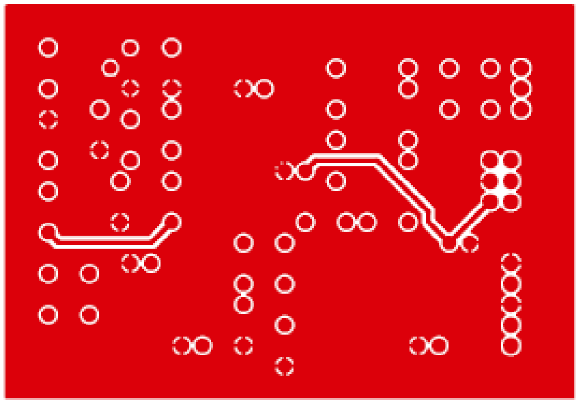

Figure D2: PCB bottom layer design