Front-end circuit design for electroencephalography (EEG) signal

S M Salahuddin Morsalin
Master's Program of Green Technology for Sustainability
Nanhua University
Chiayi County, Taiwan
s.morsalin10@gmail.com

Shin-Chi Lai
Department of Computer Science and Information Engineering
Nanhua University
Chiayi County, Taiwan
shivan0111@nhu.edu.tw

***Abstract*— Electroencephalography (EEG) signals are recorded for knowing the electrical activity of the brain from the scalp, and the recorded waveform provides acquits into the dynamic aspects of brain activity. This study incorporates the circuit design and device development to achieve the Electroencephalography signal acquisition front-end circuit design for future Brain-Computer Interface (BCI) applications. The amplitude of acquired signals should be strong enough and is usually expressed in the unit of millivolts. The data acquisition procedure consists three stages: 1) The acquisition of original EEG signal can be done by the active electrode and an instrumentation amplifier with a smaller gain; 2) Improves the signal quality by using band-pass filter and band-stop filter; 3) Those EEG signals convert into the digital code through the analog-to-digital converter (ADC) that will be integrated into a micro-controller. The digital code is stored into an embedded memory and is further transmitted via the Bluetooth module. The experimental results show that the system could implement the acquisition and storage of the EEG signals efficiently. The size of the printed circuit board (PCB) for the proposed design is smaller than 5.5 cm2. This system would be a benefit to all involved in the use of EEG for clinical diagnosis and monitoring, or even for the brain-computer interface.**

Keywords*— *Electroencephalography (EEG), Brain Computer Interface (BCI), Front-end circuit design, Printed Circuit Board (PCB), Amplifier and Electrodes, Driven Right Leg (DRL), Common-Mode Rejection Ratio (CMRR)

I. INTRODUCTION

The brain is the largest and noteworthy complex organ that control all functions of the body, interprets information from the inside and outside through embodies in mind and soul. Intelligence, creativity, emotion, memory and many more things are governed by the brain. The brain functions can be monitored through observing the electrical signal that generate in the neurons. Depending on the various location of the brain there are five major brain waves distinguished by their different frequency ranges. These frequency bands are categorized from low to high and can be recognized as Delta (δ) Theta (θ), Alpha (α), Beta (β), and Gamma (γ) respectively. The signals are called Electroencephalogram that can be extracted by using electrodes and viewed using voltmeter, oscilloscope or on the computer screen and recorded the phenomenon of electroencephalography. It is a relatively simple and completely harmless method for analyzing brain activity. It detects the pattern of brain motions and translates them into commands given as input for the external device. These signals are roughly ranged from 0.1 Hz to more than 100 Hz and measured with electrodes placed on the scalp. The amplification subsystem is first discussed and this consists of a very high common-mode rejection ratio (CMRR) instrumentation amplifier and the second gain stage.

Since Hans Berger, a German psychiatrist succeeded in recording the first human electroencephalogram and known as the inventor of electroencephalography (EEG) in 1924 [1], a lot of research work on it has been done by various researchers around the world. An increasing number of research activities and different types of studies in brain-computer interface systems (BCI) and shows the potential in this research area [2]. Hereafter, an amplification module is required to amplify these small potentials to an acceptable level. In this paper, we introduced the EEG recording circuit design and simulation, signal characteristics and the overall framework of the EEG read-out circuit. Then, we illustrate the details of the circuit design.

II. EEG SIGNAL

A. Signal Characteristics

EEG signal generates the current flow between the brain and cells in the cerebral cortex region of the brain. When neurons are active mood, current flow between dendrites due to their synaptic excitation. The current generates a magnetic field and a secondary electric field. The magnetic field is measurable by using electromyogram machines, and the electric field is measured by the EEG system through scalp electrodes. For obtaining basic brain patterns of individuals, subjects are instructed to close eyes and keep relaxation. Brainwave patterns of wave shapes that is a commonly sinusoidal wave. Usually, the signals are measured from peak to peak and normal range from 5~200uV in amplitude. In the power spectrum contribution of sine waves with different frequencies, we can obtain the electrical activity through electrodes placed on the scalp. Based on different frequency bands (0.1~ 100Hz), EEG signals considered into 5 specific classifications of brain activity which have been commonly discussed in EEG literature: Delta, Theta, Alpha and Beta as shown in Table. I and Gama waves frequencies are greater than 14Hz:

This is because in relaxation or drowsiness condition alpha activities rises and in normal state of wakefulness with open eyes beta activities is dominant and if the subject is sleep, the power of lower frequency bands is increase [3].

B. Noise Cancellation Process

TABLE I. CLASSIFICATION OF BRAIN WAVE SIGNALS

Brain Waves	Frequency	Mental conditions
Delta Wave	0.5-4 Hz	Deep sleep
Theta wave	4-8 Hz	Light sleep
Alpha wave	8-13 Hz	Awake, relaxed
Beta wave	Above 13 Hz	Concious, exited

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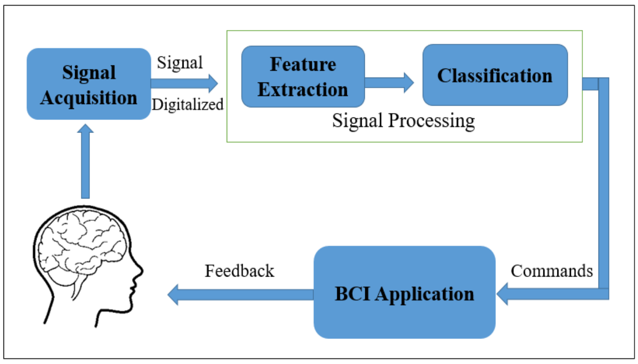

Fig. 1. The block diagram for a BCI system.

The human head consists of various layers including the brain, skull, scalp and other thin layers in between. The level of attenuation due to the skull is approximately a hundred times greater than that of the soft tissues. While recording EEG signals internal and external noise can be increase while EEG signals recorded from the scalp. Although, only a large number of active neurons can generate the potential recordable signal. These signals have to be amplified for further processing. An EEG signal normally has a typical amplitude in the range of 5~200uV. However, to reduced noise, we follow these steps of motion artifact and its equations.

Motion artifact [4] is seen as the most common artifact in bio-signal measurement. It refers to the half-cell potential difference which appears across the electrodes, whereas the half-cell potential is produced by a chemical reaction that occurs at the electrolyte-electrode interface. Thus, the root cause of the motion artifact is the electrolyte-electrode interface. However, the electrolyte electrode interface is inevitable, as long as we are using an electrode to obtain an EEG signal. So, only one way we can do is to choose an electrode with very low half-cell potential [5].

Power line interference is a significant source of noise. The power lights and the computer used to monitor the EEG signals that can produce the power line interference. More specifically, this noise imposes a serious impact on the raw EEG signal in magnetic and electric fields [6]. Concerning the power line noise arising from the magnetic field, we used the electrode line in twisted-pair form to reduce the loop surface area which is made of electrodes lead wires, the human body, and pre-amplifier.

III. Brain Computer Interface

A Brain-Computer Interface (BCI) as shown in Fig. 1 is a system that acquires and analyzes neural signals through some steps translates neuronal information into commands capable of controlling external software and hardware such as a computer to achieve the goal of creating a communication channel directly between the brain and the computer. Therefore, Mr. Jonathan Wolpaw doctors New York State Department of Health proposed a brain-computer interface system consisting of three elements: measuring signal acquisition, extracting feature extraction, and converting into a translation algorithm. As shown in the system block diagram [7]. In some cases, it is possible to distinguish persons only according to their typical brain activity.

EEG signals are recorded for 20-40 minutes and get the record by placing electrodes at various positions on the scalp.

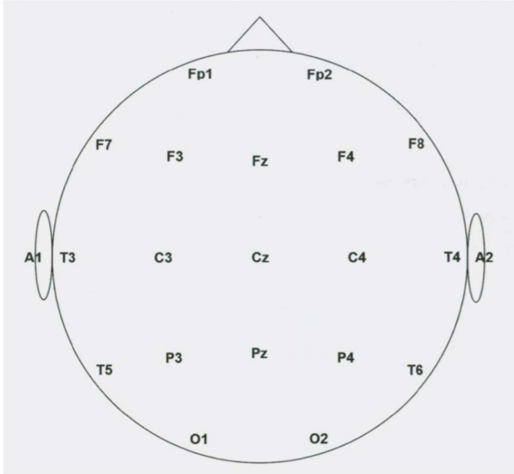

Fig. 2. Standard placement of electrodes on scalp.

The head is divided into proportional distances from prominent skull landmarks (nasion, preauricular points, and inion) to provide adequate coverage of all regions of the brain. Electrode placements are labeled according to adjacent brain areas: F (frontal), C (central), T (temporal), P (posterior), and O (occipital). Fig. 2 shows the schematic view of scalp and conventional electrode arrangement recommended by the International Federation of Societies for Electroencephalography and Clinical Neurophysiology [8]. For the single-channel data acquisition process, a positive electrode is placed on the Fp2 position, a reference electrode is placed on the Fp1 position and the negative electrode is placed on the A1 (earlobe) position.

IV. EEG Signal Acquisition Method

The circuit analyzing unit has been designed to amplify the EEG signal for advance exemption. The signals are confined in the frequency range 0.1 to more than 100 Hz, according to the EEG signals circuit. The band pass filter and band stop filter have been designed for cut off frequency range. A notch filter also has been considered while designed the band-stop filter for better performance, reduce noise and remove power line interference. After design, all filters and circuits, a post-amplifier for further amplification of EEG signal and voltage adder has been designed for signal keep in optimistic domain [9]. Fig. 3 shows the block diagram of a general EEG signal acquisition system which is mainly collected alignment of scalp electrodes, instrumentation amplifier, band pass filter and band stop filter, post-amplifier, and the output display.

A. Instrument Amplifier

An instrumentation amplifier is an integrated circuit (IC) used to amplify the signal, which is a type of differential

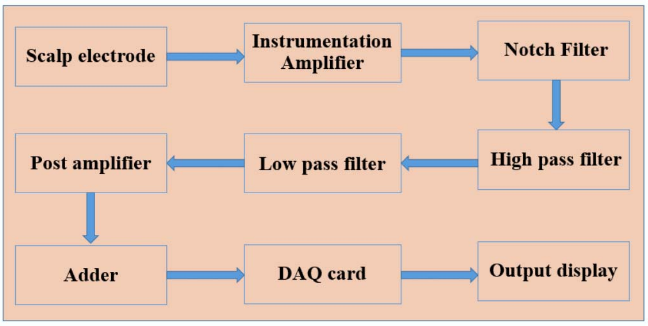

Fig. 3. The block diagram of EEG acquisition system.

amplifier because it amplifies two input signals. The ability to reject noise or unwanted signals common to all IC pins is called the common-mode rejection ratio (CMRR) [10]. The designed instrumentation amplifier is performed as front cease of the EEG signal acquisition system. To design the schematic layout of the instrumentation amplifier the INA 333 has been used for signal acquisition circuit. The INA333 is laser trimmed for very high common-mode rejection (100 dB at G ≥ 100. The DRL circuit was utilizing and adding the high CMRR instrument amplifier with differential inputs, and followed by a modified high-Quality factor, active Twin-T notch filter ((fc Notch = 60 Hz, − 38 dB) [11]. The CMRR is a measure of how well the device rejects a common-mode signal through referring equation (1)

$$\text{CMRR}= \frac{\text{Ad}}{\text{Acm}} \tag{1}$$

It's simply the ratio of the differential gain Ad over the common-mode gain Acm. Differential Gain, Ad = Vo / (v+ - v-), This is your basic open-loop gain of an op-amp. Common-Mode Gain, A cm = Vo / V cm, Here's the gain with the inputs tied together at Vcm = V+ = V-. Putting the value of CMRR in equation (2) we can get the value of CMR.

$$\text{CMR} = 20 \log10 (\text{CMRR}) \text{ dB} \tag{2}$$

The CMR behavior developed here is somewhat oversimplified in a number of ways. The actual error in a real op-amp results from the imbalances in the transistors and resistors of the input stage.

The INA333 measures small differential voltage with high common mode voltage developed between the non-inverting and inverting input. The high input impedance makes the INA333 suitable for a wide range of applications. The ability to set the reference pin to adjust the functionality of the output signal offers additional flexibility that is practical for multiple configurations. The INA333 device is a low-power, precision instrumentation amplifier offering excellent accuracy. The versatile 3-operational amplifier design, small size, and low power make it ideal for a wide range of portable applications. The device can be configured to monitor the input differential voltage when the gain of the input signal is set by the external resistor RG. The output signal references to the Ref pin. All the points are connected according to the pin configuration of the INA 333 amplifier.

B. Voltage and Gain Calculation

The gain of the particular instrumentation amplifier can be calculated by this industry standard Gain equation (3). Gain of the INA333 device is set by a single external resistor

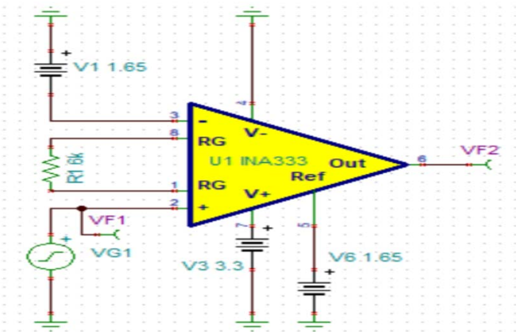

Fig. 4. Functional diagram of Instrumentation amplifier.

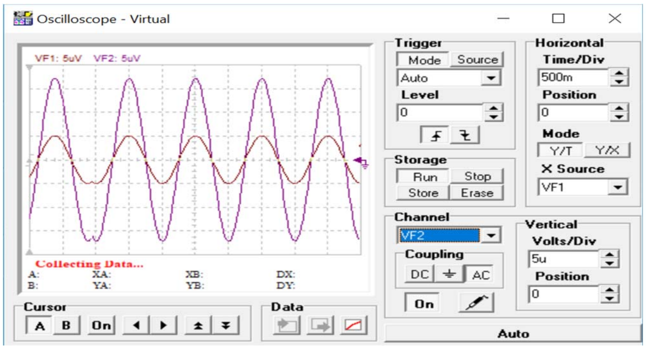

Fig. 5. Output signal of instrumentation amplifier.

RG, connected between pins 1 and 8. The value of RG is selected according to equation (3).

$$G = 1 + (100\text{k}\Omega / \text{RG}) \tag{3}$$

Where RG is the external resistor [12]. Here, we set RG = 6kΩ to be an example. Hence, the gain of the amplifier is G= 17.6, after getting the gain of instrumentation amplifier, the value of G is taken to the equation (4) got the output of Instrumentation amplifier circuit.

$$V= G^* (\text{Vin+} - \text{Vin-}) \tag{4}$$

Whereas, the positive input value is 5uV and the negative input value is 1.65V these value put in the equation (4) than we will get output voltage. Where, gain G = 17.6, positive input voltage Vin+ = 5uV negative input voltage Vin- = 1.65v Output voltage, V out = 2917mV. Fig. 4 shows the circuit diagram of instrumentation amplifier and Fig. 5 shows the output signal of instrumentation amplifier.

C. Notch Filter

A Notch Filter is also known as a Band Stop filter or Band Reject Filter. Since it consists of two 'T' shaped networks, it is mentioned as a twin T network. The Notch filter divides the signal into two parts, one part is considered low, the other part is filtered out, and the two are mixed together. The frequency of the concave is set by the frequency of the notch filter [13]. By using this notch circuit, we can eliminate single frequency at 50 or 60 Hz. The second-order notch filter with active component op-amp is in the non-inverting configuration. The twin T notch filter calculator computes the values to obtain a notch frequency as entered by the user. The notch frequency is the frequency that is most greatly attenuated by the circuit. The twin-T network is used as a band stop filter for a particular selection of component values. At the very high and very low frequencies, the band stop filter circuit acts as an open circuit, whereas the mid frequencies the circuit acts as a short circuit. It is commonly used for attenuation of a single frequency such as 60 Hz power line frequency [14].

D. Band Stop Filter

The band stop filter has been designed by using the combination of low pass and high pass filter with the parallel connection as an alternative cascading connection. For band reject response, the low cutoff frequency of the high-pass filter must larger than the excessive cut-off frequency of the low pass filter. If this band stop is very slight and highly attenuated over a few Hz, then the band stop filter is greater generally referred to as a notch filter, as the frequency response shows that of a deep notch with excessive selectivity instead of a flattened wider band. The frequency response of the stop band is obtained as Band Pass filter Fig. 6 given below.

E. Band Pass Filter

The main distinguishing feature of a band pass filter is its ability to pass frequencies relatively attenuated over a specified band or spread of frequencies. The raw EEG signal is overlapped with mixed frequency noises, to overcome these noises a desirable high pass filter has to be designed. This design has the advantage of producing a relatively irregular pass band frequency response with one half representing the low pass response and the other half representing high pass response. For the low pass filter, this band starts passing from zero Hz and continues until it reaches the resonant frequency from the most ignored band gain [15]. Through rearranging the value and positions of the resistors, capacitors inside of filter we can produce a good deal better as shown in Fig. 7.

F. The Gain Stage Amplification

In respect to design high quality of EEG signals amplifier, the gain stage post-amplifier must have high input impedance, high common-mode rejection ratio, low noise, small non-linearity, strong anti-interference ability, the appropriate frequency and the range of dynamic, which makes the design of an amplifier that is very difficult, but it is the most important to design a circuit of acquisition of the total system EEG signals. Using the formula (5) to calculate the output voltage gain of a potential divider network through, we can calculate the closed-loop voltage gain of gain stage amplifier of the Non-inverting amplifier as shown in Fig. 8.

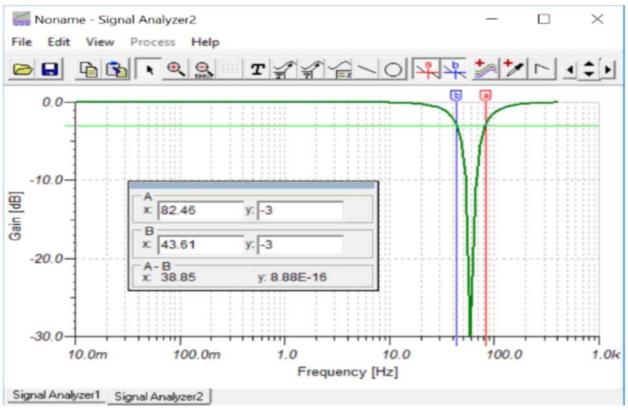

Fig. 6. Band stop signal frequency response.

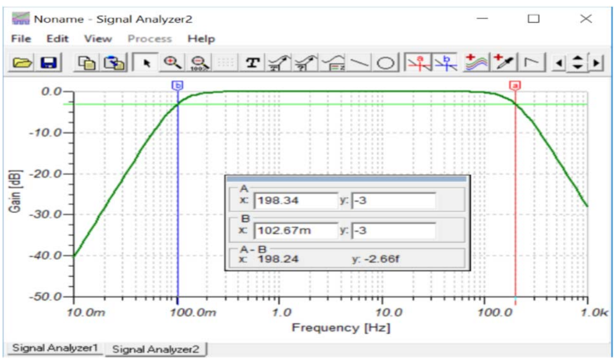

Fig. 7. Frequency response of band pass filter.

$$\text{Voltage gain, G gain} = \left(1+\frac{R1}{R2}\right) \tag{5}$$

Where R1 is the feedback resistance and R2 ground resistance of the gain stage amplifier circuit. Through the rearranging value of feedback resistance and ground resistance, can set value for our expected voltage gain. The input signal of gain stage amplifier and voltage output signal shows in the Fig. 9.

EEG signals are very easily affected due to interference of the power frequency and the radio frequency, and these signals are easily into input through pins 4 and 5 the brain electrode in the pin configuration figure, which can be suppressed by improving the amplifier resistance [16]. For INA 333, the voltage gain of resistance when access to pins 1 and 8 more than 100 dB, the common-mode rejection ratio is greater than 120dB, the circuit is up to 200dB, to meet the EEG of the common-mode rejection ratio of not less than the requirements of 120 dB.

V. Propose Method for EEG Signal Acquisition

The signal acquisition circuit system has included signal amplifying as pre-amplifiers, filters design, gain amplifiers and so on. The acquired EEG signal is amplified using precision instrumentation amplifier INA 333 (TINA IT). An outstanding conventional electrode has been used for this system. Three electrodes are sufficient to acquire the EEG signal compared to the 10-20 system. It is less complicated in terms of analysis and data processing. In our system, we will use disposable metal buckle electrodes. One electrode is placed at the center of the forehead as a reference electrode. Two electrodes are placed at the left and right of the forehead. The left electrode is connected to the inverting terminal (pin 1) and the right electrode is connected to the non-inverting terminal (pin 2) of the system. The electrodes will be connected to the device via buffer amplifiers or voltage.

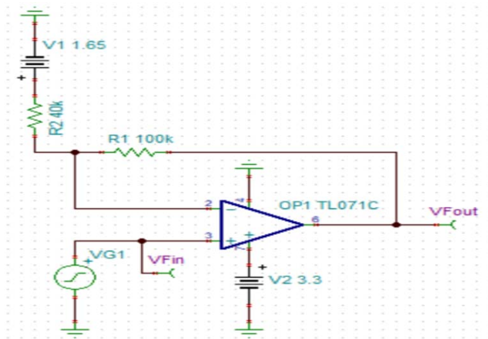

Fig. 8. Gain stage post amplifier circuit.

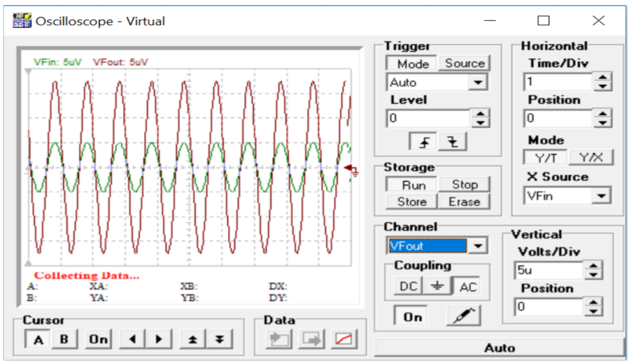

Fig. 9. Gain stage amplifier output signal.

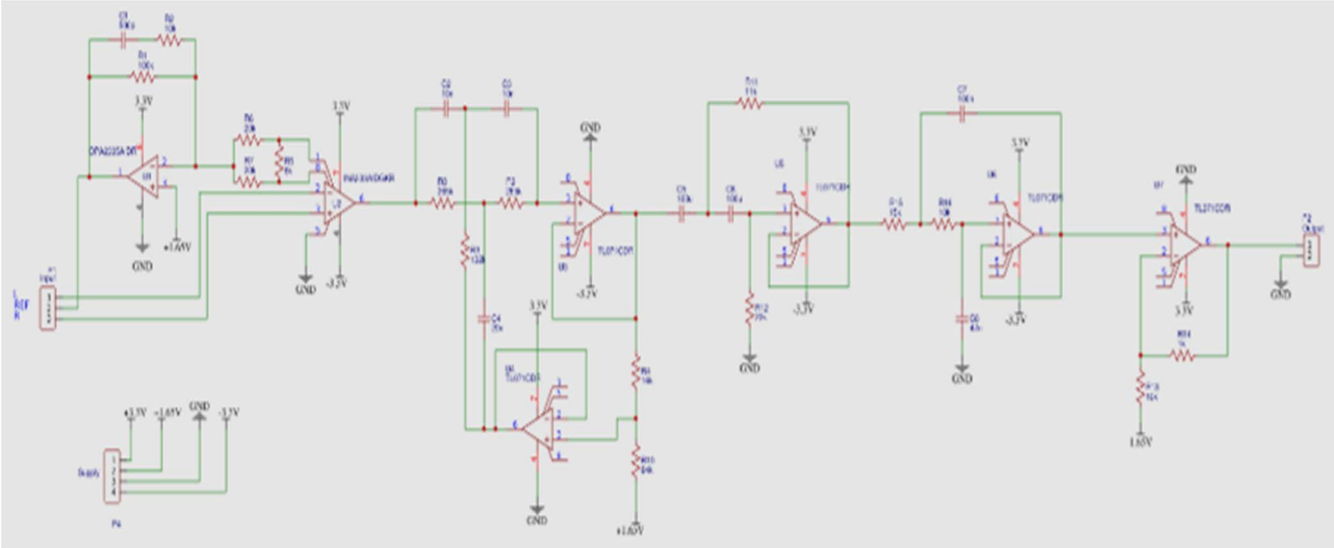

Fig. 10. Schematic diagram of EEG signal circuit.

A. Schematic Circuit Diagram

The schematic diagram of the EEG circuit system (see Fig. 10) added the different parts of the Instrumentation amplifier, the INA333 is a low-power, zero-drift instrumentation amplifier offering excellent accuracy. The versatile three operational amplifier design and small size make the amplifiers ideal for a wide range of applications. Zero drift chopper circuitry provides excellent DC specifications. Driven right leg circuit, biological signal amplifiers to reduce Common-mode interference added with an instrumentation amplifier. Biological signal amplifiers such as Electroencephalogram circuits measure very small electrical signals emitted by the body, often as small as several micro-volts (millionths of a volt). Unfortunately, the patient's body can also act as an antenna which picks up electromagnetic interference, especially 50/60 Hz noise from electrical power lines. This interference can obscure the biological signals, making them very hard to measure. Right Leg Driver circuitry is used to eliminate interference noise by actively canceling the interference.

B. Circuit Layout Design

Mechanically supported and electrically connected electronic components using conductive tracks, pads and other features etched from one or more sheet layers of copper laminated between sheet layers of a non-conductive substrate. Before starting the PCB design we must check those following steps to complete work smoothly.

- PCB board design and planning.
- PCB sample test.
- PCB product certification operation.
- Familiar with surface adhesion technology.
- PCB sample follow-up test and test.
- Electronic parts product information collection.
- Preliminary investigation of irregular conditions.
- Product reliability testing and problem analysis.

Printed circuit board layout showed in Fig. 11.

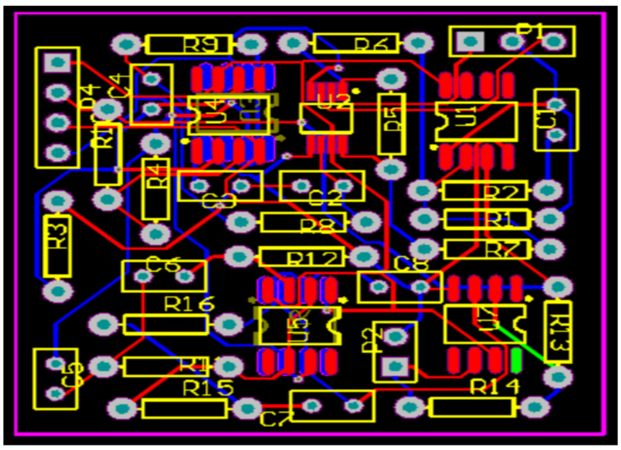

Fig. 11. PCB layout for EEG signal acquisition circuit.

VI. Result and Discussion

EEG signal acquisition system circuit design and spectrum analysis has been done in this paper, and Table II shows comparison with another paper. The FEC of each consists of an off-the-shelf instrumentation amplifier gain=17.6, and output voltage VO= 2971mV an active notch filter fc = 60Hz, 2nd order active Butterworth low-pass filter followed by a passive low pass filter fc = 47.5 Hz, gain = 1.61 and a passive high pass filter fc = 0.16 Hz.

The acquisition system has been done by using the TINA TI and Altium Designer to design PCB layout. Electrodes read the signal from the head surface, amplifiers bring the microvolt signals into the range where they can be digitalized accurately, converter changes signals from analog to digital form, and personal computer stores and displays obtained data. Selecting reference electrode point and adding Driven Right Leg (DRL) circuit was most challenging while design Front-end circuit simulation because of the electroencephalogram (EEG) is recorded from electrodes on the human scalp. For high-density EEG systems, data processing can take a significant amount of time, even on large computing clusters. Lastly, more electrodes mean higher costs and more difficult experimental setups. Selecting reference electrode point and adding Driven Right Leg (DRL) circuit was most challenging while design Front-end circuit simulation because the electroencephalogram

TABLE II. EXPERIMENT AND RESUL COMPARISON

Experiment and Result Comparison	Neuro-Monitor: A low-power, wireless, wearable EEG device with DRL-less AFE (Other paper)	Front-end circuit design for electroencephalography (EEG) signal (My Experiment)
DRL circuit	DRL circuit eliminated	DRL circuit added with amplifier
T-win-T notch filter	Notch (fc) = 60 Hz, −38 dB	Notch (fc) = 60 Hz, −38.9 dB
Low-pass filter	Cut off frequency fc = 125 Hz	Cut off frequency fc= 122Hz
High pass filter	Cut off frequency fc= 0.5 Hz	Cut off frequency fc=0.16Hz
Overall gain	55.84 dB	48.50 dB
PCB Size	11.135 cm2	Less than 5.5 cm2
Gain	19.7	17.6

(EEG) are recorded on the oscillations of brain electric potentials acquired from electrodes on the human scalp.

Selecting reference electrode point and adding Driven Right Leg (DRL) circuit was most challenging while design Front-end circuit simulation because the electroencephalogram (EEG) are recorded on the oscillations of brain electric potentials acquired from electrodes on the human scalp. Electric potentials are the direct consequence of the existence of electric dipoles created by the postsynaptic potentials generated at apical dendrites of pyramidal cells in the cortex. The poles of the electric dipole can be seen as the source and sink of ionic currents created by the excess and defect of captions at soma and apical dendrites, respectively.

VII. CONCLUSION

In this paper, we describe the method of constructing an Electroencephalography (EEG) signal acquisition system. Trying to improve the signal quality and acquisition system by using band-pass filter and band-stop filter due to the further use in the brain-computer interfacing (BCI) system development. We use DRL circuit, which allows independent channel design for the EEG system as for the reference electrode. This used to utilize very low-noise, high CMRR instrument amplifier followed by active notch filter to suppress the common-mode noise. From the experimental observation, it can be said that the designed system can be implemented for the EEG signal acquisition and storage of data to Computer efficiently. We have finished circuit simulation and got output signals from the schematic diagram and designed PCB layout of the circuit.

The future work for this project can be divided into two parts. One part could be to expand the EEG three electrodes practical experiment. Several EEG circuits have constructed for that as each circuit takes in only two input electrodes and one ground electrode. All the circuits could be made on a single Printed Circuit Board (PCB) for as many EEG electrodes that one needs to use as that would reduce the noise in the signal. For further use of the system in case of BCI application, the different signal processing tools like feature extraction by using FFT (Fast Fourier Transform) or Wavelet Analysis and for training of the EEG data set Neural Network or SVM (Sample Vector Machine) would be a benefit to involved the use of EEG for clinical diagnosis and monitoring, or even for Brain-Computer Interface.

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