Development of a Low-cost, Compact, Wireless, 16 - channel Biopotential Data Acquisition, Signal Conditioning and Arbitrary Waveform Stimulator System

Doctoral Thesis

By

"Rajat Suvra Halder"

(2019BMZ0008)

DEPARTMENT OF BIOMEDICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY ROPAR

June, 2025

Development of a Low-cost, Compact, Wireless, 16 - channel Biopotential Data Acquisition, Signal Conditioning and Arbitrary Waveform Stimulator System

A Thesis Submitted

In Partial Fulfillment of the Requirements

for the Degree of

DOCTOR OF PHILOSOPHY

by

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June, 2025

Rajat Suvra Halder*: Development of a low-cost, compact, wireless, 16 - channel biopotential data acquisition, signal conditioning and arbitrary waveform stimulator system*

Dedicated

to

My

Family

Declaration of Originality

I hereby declare that the work, which is being presented in the thesis, entitled "***Development of a Low-cost, Compact, Wireless, 16 - channel Biopotential Data Acquisition, Signal Conditioning and Arbitrary Waveform Stimulator System",*** has been solely authored by me. It presents the result of my own independent investigation/research conducted during the time period from August, 2019 to March, 2025 under the supervision of Dr. Ashish Kumar Sahani, former Assistant Professor, Department of Biomedical Engineering, IIT Ropar, Rupnagar and Dr. Rajesh Kumar, Assistant Professor, Department of Biomedical Engineering, IIT Ropar, Rupnagar. To the best of my knowledge, it is an original work, both in terms of research content and narrative, and has not been submitted or accepted elsewhere, in parts or in full, for the award of any degree, diploma, fellowship, associateship, or similar title of any university or institution. Further, due credit has been attributed to the relevant state- of-the-art and collaborations with appropriate citations and acknowledgments, in line with the established ethical norms and practices. I also declare that any idea/data/fact/source stated in my thesis has not been fabricated/ falsified/ misrepresented. All the principles of academic honesty and integrity have been followed. I fully understand that if the thesis is found to be unoriginal, fabricated, or plagiarized, the institute reserves the right to withdraw the thesis from its archive and revoke the associated degree conferred. Additionally, the institute also reserves the right to appraise all concerned sections of the society of the matter for their information and necessary action. If accepted, I hereby consent for my thesis to be available online in the Institute's Open Access Repository, inter-library loan, and the title and abstract to be made available to outside organizations.

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Certificate

This is to certify that the thesis, entitled **"Development of a Low-cost, Compact, Wireless, 16 -channel Biopotential Data Acquisition, Signal Conditioning and Arbitrary Waveform Stimulator System"**, submitted by **Rajat Suvra Halder (Entry # 2019BMZ0008)** for the award of the degree of **Doctor of Philosophy** of the Indian Institute of Technology Ropar, Rupnagar, is a record of original research work carried out under my guidance and supervision at the Department of Biomedical Engineering, IIT Ropar, Rupnagar. All other sources of information, material, and mentorship have been acknowledged at appropriate places in the thesis. To the best of my knowledge and belief, the work presented in this thesis is original and has not been submitted, either in part or full, for the award of any other degree, diploma, fellowship, associateship or similar title of any university or institution.

In my opinion, the thesis meets the requirements of the regulations relating to the award of PhD degree.

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Lay Summary

Biopotential signals such as EMG, EEG, ECG, and EOG are essential for health monitoring and disease diagnosis. However, most existing biopotential data acquisition (Bio DAQ) systems are wired, limiting mobility and comfort, and are often designed for specific signals, making them unsuitable for multi-signal acquisition or animal studies. Wireless Bio DAQ systems provide greater flexibility, but existing designs still face challenges in adaptability and signal diversity.

This study presents a compact, 16-channel wireless Bio DAQ system integrated with an electrical stimulator, incorporating several innovative features: (1) user-selectable digital filters per channel for simultaneous multi-signal acquisition, (2) selectable gain with a configurable analog filter, (3) support for multi-subject monitoring (up to four patients), (4) compatibility with both two-electrode and three-electrode configurations, and (5) an integrated stimulator generating charge-balanced biphasic waveforms with selectable pulse duration and frequency.

The system was rigorously tested using simulators and real-life biopotential signals and evaluated for safety, including electrical safety and electromagnetic interference (EMI) tests, ensuring compliance with medical standards. The results confirm the system's reliability, adaptability, and enhanced user comfort compared to existing devices.

The thesis is structured into five chapters, covering an introduction to biopotential signals and existing Bio DAQ systems' limitations, a literature review, circuit development, prototype development & testing, and finally, conclusions and future perspectives. This work represents a significant advancement in wireless Bio DAQ systems by integrating flexible hardware and advanced signal processing techniques to improve usability and safety.

Abstract

Biopotential signals or biosignals, including ECG, EMG, EEG, and EOG, play an important role in assessing human health, aiding in disease diagnosis, and monitoring physiological conditions. However, most commercially available biopotential data acquisition (Bio DAQ) systems are wired and designed for specific signals, resulting in limitations such as discomfort during extended use and incompatibility with animal studies. Wireless Bio DAQ systems represent a significant technological advancement, offering improved flexibility and enhanced user comfort. While various Bio DAQ systems are available in the market, most are optimized for individual signal types like EMG, ECG, or EEG, with predefined amplifier gains and filter frequencies, making them unsuitable for capturing multiple biosignals simultaneously. Additionally, wired systems are impractical for animal studies. Several design approaches have been explored for developing wireless Bio DAQ devices.

In this study, we present a compact, 16-channel wireless biopotential data acquisition (Bio DAQ) system integrated with an electrical stimulator. Our proposed design incorporates multiple innovative and flexible features: (1) Each channel includes user-selectable digital filters, optimized for specific signal frequencies such as EMG, ECG, EEG, and EOG, enabling simultaneous multi-signal acquisition. (2) The system features variable gain functionality combined with an upgradable analog bandpass filter. (3) It supports multi-subject monitoring by acquiring biosignals from up to four patients simultaneously. (4) Both two-electrode and three-electrode configurations are supported for signal acquisition. (5) The integrated stimulator generates a biphasic, charge-balanced, trapezoidal, stimulus output with a near-zero DC offset, along with user-configurable pulse duration and stimulus frequency options.

The developed system underwent extensive testing using both simulators and real-life biopotential signal acquisitions. Additionally, it was subjected to rigorous safety evaluations, including electrical safety testing and electromagnetic interference (EMI) testing, in accordance with international standards, ensuring compliance with medical device safety regulations. The proposed system marks a substantial improvement over existing technologies by combining reconfigurable hardware with cutting-edge signal processing methods.

The thesis is structured into five chapters. **Chapter 1** serves as an introduction, provides an overview of biopotential signals (ECG, EOG, EEG, EMG) and the limitations of existing Bio DAQ systems. It outlines the specific objectives of this research. **Chapter 2** provides an extensive literature review on wireless Bio DAQ system with future scope for development. In **Chapter 3,** we have discussed the development of the circuit for various sub systems like Analog Front End (AFE), Wireless Module, Microcontroller Unit (MCU), Stimulator Module, Power Supply, and Display Unit. **Chapter 4** details the development of a fully functional prototype by integrating key subsystems. The process begins with circuit implementation on a breadboard, followed by iterative testing, and culminates in a compact, single PCB module. The chapter also covers the testing and results to validate the prototype's effectiveness, demonstrating its capability to acquire high-quality

biopotential signals and meet its intended objectives. **Chapter 5** discussed the conclusions and future perspectives of this work.

Keywords: Biopotential, data acquisition, stimulator, wireless, portable.

List of Publications

Journal papers

1. **R. S. Halder**, B. Basumatary, A. K. Sahani, "Development of a Low-cost, Compact, Wireless, 16 - channel Biopotential Data Acquisition, Signal Conditioning and Arbitrary Waveform Stimulator," *Biomedical Physics & Engineering Express, 2023. DOI: 10.1088/2057-1976/ad17a8*
2. **R. S. Halder**, B. R S Halder, B. Basumatary, R Kumar, A K Sahani, "A Systematic Review on Wireless Biopotential Signal Acquisition Devices Journal*," IETE Technical Review. (Under Review).*
3. **R S Halder,** B. Basumatary, R Kumar, A K Sahani, "Development of a Portable, Wireless, Multi-channel Physiograph with Integrated Stimulator." *IETE Journal of Research (Under Review)*
4. B. Basumatary, **R. S. Halder**, C. Singhal, A N Mallick, A Khokhar, R. Bansal, A. K. Sahani, "Deep Learning Approach for Gait Detection for Precise Stimulation of FES to Correct Foot Drop", *IETE Technical Review*, 2024. *DOI: https://doi.org/10.1080/02564602.2024.2344779*
5. B. Basumatary, **R. S. Halder**, A N Mallick, A Khokhar, R. Bansal, R. Kumar, A. K. Sahani, "AI-Enhanced FES for Foot Drop: A Novel Biphasic Charge-Balanced Stimulation Approach". *(Submitted)*
6. Balendra, **R. S. Halder**, & Sahani, A. (2022). Improvising limitations of DNN based ultrasound image reconstruction*. Physical and Engineering Sciences in Medicine, 45(4), 1139-1151.*

Conference papers

1. **R.S. Halder,** B. Basumatary, A. Pandya, G. R. Jangir, A. K. Jain, A.K. Sahani, "EMG Based Clinical Evaluation of an Unpowered Exoskeleton Device," *IEEE Medical Measurements & Applications (MeMeA) 2023. DOI: 10.1109/MeMeA57477.2023.10171864*
2. B. Basumatary, **R. S. Halder**, A. K. Sahani, "A Microcontroller Based Charge Balanced Trapezoidal Stimulus Generator for FES System", *2021 IEEE International Instrumentation and Measurement Technology Conference (I2MTC) 2021. DOI: 10.1109/I2MTC50364.2021.9459837*
3. B. Basumatary, **R. S. Halder**, C. Singhal, A. N. Mallick, A. Khokhar, R. Bansal , A. K. Sahani, "Design of a Compact Wearable AI-driven Functional Electrical Stimulation System for Foot Drop," International Functional Electrical Stimulation Society (IFESS), 1-3 September 2024, University of Bath, UK.
4. B. Basumatary**, R. S. Halder**, C. Singha, A. K. Sahani, "Design of a Compact Wearable Functional Electrical Stimulation System for Foot Drop Correction with AI Driven Foot Lift Detection," *Bio-Remidi 2022 , IIT Guwahati.*

Book Chapters

1. B. Basumatary, **R. S. Halder**, A. K. Sahani, "Deep Learning based Foot Lift Event Detection using a Single Accelerometer for Accurate Firing of FES", *Sensing Technology*, Lecture Notes in Electrical Engineering, vol. 886, pp.31-41, Springer, ISBN: 978-3-030-98885-2. *DOI:* https://doi.org/10.1007/978-3-030-98886-9_3

Patents

1. Development of a Low-cost, Compact, Wireless, 16 - channel Biopotential Data Acquisition, Signal Conditioning and Arbitrary Waveform Stimulator System. *(Under preparation)*

Table of Contents

List of Figures

List of Tables

Notations and Abbreviations

Bio DAQ	Biopotential Data Acquisition
ECG	Electrocardiogram
EEG	Electroencephalogram
EMG	Electromyogram
EOG	Electrooculogram
ECoG	Electrocorticogram
PPG	Photoplethysmogram
GSR	Galvanic Skin Response
EDA	Endodermal Activity
BP	Blood Pressure
HR	Heart Rate
SpO2	Oxygen Saturation
DC	Direct Current
AC	Alternating Current
Tx	Transmitter
Rx	Receiver
AFE	Analog Front End
MCU	Microcontroller Unit
BJT	Bipolar Junction Transistor
Opamp	Operational Amplifier
IA	Instrumentation Amplifier
AI	Artificial Intelligence
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
DAC	Digital to Analog Converter
ADC	Analog to Digital Converter
IC	Integrated Circuit
NFC	Near Field Communication
IIR	Infinite Impulse Response
BPF	Band Pass Filter
LPF	Low Pass Filter
DRL	Right Leg Drive
LED	Light Emitting Diode
GPIO	General Purpose Input/Output
DIP	Dual in-line Package
UART	Universal Asynchronous Receiver-Transmitter
MQTT	Message Queuing Telemetry Transport
TCP/IP	Transmission Control Protocol/Internet Protocol
NC	Normal Condition
ICU	Intensive Care Unit
BCI	Brain Computer Interface
ANS	Autonomic Nervous System
OTA	Trans-conductance Amplifier
FES	Functional Electrical stimulation
PCB	Printed Circuit Board
SoC	System on Chip
FM	Frequency Modulation
FSK	Frequency Shift Keying
TDMA	Time Division Multiple Access
fNIRS	Functional Near-Infrared Spectroscopy
MCFSK	Manchester-Coded Frequency Shift Keyed
COTS	Commercially available off-the-shelf
ML	Machine Learning
IoT	Internet of Things
MEMS	Micro-Electro-Mechanical Systems
Wi-Fi	Wireless Fidelity
DSP	Digital Signal Processing
SPI	Serial Peripheral Interface
GFSK	Gaussian Frequency Shift Keying
ISM	Industrial, Scientific, and Medical
HTTP	Hypertext Transfer Protocol
AF	Atrial Fibrillation
EMI	Electromagnetic Interference
EMC	Electromagnetic Compatibility
µS	Microsecond
Hz	Hertz
Ω	Ohm
mA	Milliampere
µA	Microampere
V	Volt
mV	Millivolt
µF	Microfarad
nF	Nanofarad
cm	Centimeter
m	Meter
mW	Milli Watt
W	Watt
mAh	Milliampere-hour
KB	Kilobyte

CHAPTER - 1
Introduction

Chapter 1
Introduction

1.1 Biopotential

Biopotential refers to the electrical potential differences generated by biological processes within living organisms. These potentials are crucial for communication and signaling in the body, particularly in the nervous and muscular systems. The origin of biopotential lies in the fundamental properties of cells and the electrochemical processes at their membranes [1].

Biopotential signals or biosignals are electrical signals produced by the physiological activity of living cells, tissues, and organs. They result from ionic currents flowing through cellular membranes and are commonly used to monitor and analyze the functions of the nervous, muscular, and cardiac systems. To measure these ionic potentials or signals, they need to be transformed into electronic signals. This is achieved using electrodes, which transform ionic potentials into electronic potentials, which are commonly known as biosignal or biopotential signal. These electrodes are used to detect signals produced by various parts of the body [2].

1.2 Origin of Biopotential Signals

The connection between electricity and medical science can be traced back to the 18th century when Luigi Galvani discovered that various physiological processes are associated with electrical activity. His pioneering work laid the foundation for the study of bioelectricity, leading to significant advancements in medical diagnostics and treatment. This discovery laid the foundation for understanding the functions of living tissues in terms of bioelectric potentials. It is now well-established that the human body, composed of living tissues, acts as a power source, generating various electrical signals from muscles and nerves. Normal muscle contractions involve ion migration, creating measurable potential differences through appropriately placed electrodes. For instance, the heart and brain generate distinct voltage patterns that, when recorded and analyzed, provide valuable insights for clinical practice and research. Additionally, electrochemical changes during nerve signal conduction to and from the brain also generate potential differences. These signals, typically in the microvolt range, produce intricate patterns of electrical activity when recorded [3].

Biopotential signals originate at the cellular level, with their source being ionic in nature. Each cell functions as an ionic conductor, separated from its external environment by a semipermeable membrane. This membrane acts as a selective filter, allowing certain ions to pass through freely while restricting others. All living organisms are composed of various types of cells. In humans, cells can range in size from 1 micron to 100 microns in diameter, with lengths spanning from 1 millimeter to 1 meter, and a typical membrane thickness of approximately 0.01 micron [3].

The cells in the body are surrounded by ionic body fluids that act as a conductive medium for electrical potentials. The primary ions responsible for generating cell potentials are sodium (Na^+), chloride (Cl–) and potassium (K+). The membranes of excitable cells allow the movement of K+ and Cl– ions relatively easily but restrict the flow of Na+, even when a significant concentration gradient of sodium exists across the membrane. Consequently, sodium ions are more concentrated outside the cell membrane than inside. This distribution creates a negative charge along the inner surface of the cell membrane and a positive charge along the outer surface. This unequal charge distribution arises from specific electrochemical reactions and processes within the living cell, resulting in a potential difference known as the resting potential. A cell in this state is referred to as polarized. Any reduction in the resting membrane potential difference is termed depolarization [3].

The arrangement of positively charged ions on the outer surface of the cell membrane and negatively charged ions on the inner surface generates a potential difference across the membrane. This electrochemical gradient effectively transforms the cell into a miniature biological battery, playing a crucial role in nerve impulse transmission and muscle contractions. Research indicates that the internal resting potential of a cell is approximately –90 mV relative to the outside [3]. Upon excitation or stimulation, the outer surface of the cell membrane momentarily becomes negative compared to the interior, a process known as depolarization, during which the cell potential shifts to approximately +20 mV. Shortly after, repolarization occurs, restoring the cell to its normal state, where the interior becomes negative again relative to the exterior. This process is essential for re-establishing the resting potential. The continuous cycles of depolarization and repolarization generate voltage waveforms, which can be captured using appropriate microelectrode techniques. An example of such a waveform is illustrated in Fig. 1.1.

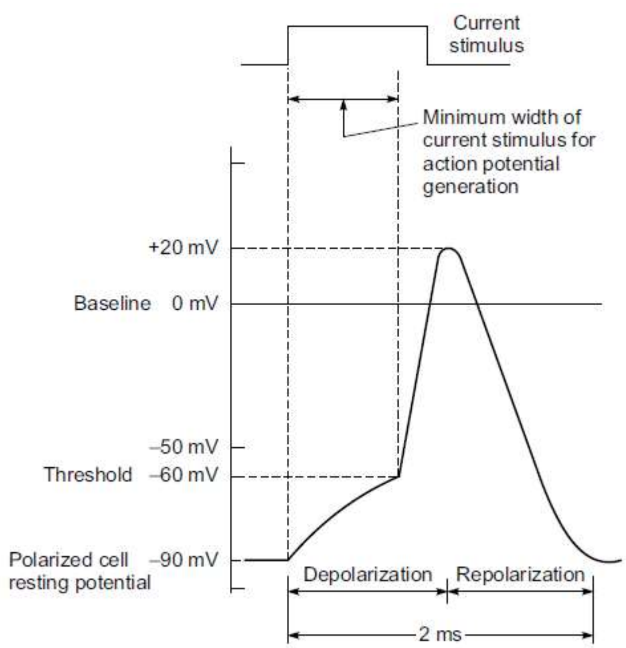


Figure 1.1 A Typical Biopotential Waveform [3].

Each time a muscle contracts (or moves), it generates an electric voltage. This voltage appears in the muscle such that the contracting muscle section is always negative in relation to its surroundings. These voltages, known as *action potentials*, are produced by the muscle's activity. Once the contraction is completed, repolarization occurs, leading to muscle relaxation and its return to the original state.

1.3 Different Types of Biopotential Signals

The biopotential signals of clinical importance are typically generated by the coordinated activity of large groups of cells. During synchronized excitation of many cells, charges move through body fluids toward areas of the body that have not yet been excited. This migration of charges creates an electric current, which results in potential differences across various parts of the body, including its outer surface. These potential differences can be easily detected by placing electrodes at two points on the body's surface and measuring them with a sensitive instrument. These recorded potentials are crucial for diagnosis and therapeutic purposes. These electrodes, often referred to as biosignal or biopotential electrodes, are used to capture signals generated by different parts of the body. These signals vary in amplitude, frequency, and other characteristics depending on their source. Common examples include electroencephalogram (EEG), electrocardiogram (ECG), electrooculogram (EOG), photoplethysmogram (PPG), electromyogram (EMG), electrocorticogram (ECoG), and galvanic skin response (GSR). Table 1 provides an overview of these biosignals and their unique properties [2,4].

Table 1.1 Different types of Biopotential signals generated from human body

Name of Signal	Origin	Amplitude	Frequency
Electrocardiogram (ECG)	Heart	0.5-4mV	0.01-250Hz
Electroencephalogram (EEG)	Brain	5-300μV	0-150Hz
Electromyogram (EMG)	Muscle cells	0.1-5mV	0.0-10000Hz
Electrooculogram (EOG)	Eye	0.05-3.5mV	0-50Hz
Electrocorticogram (ECoG)	Brain(intracranial)	100-200μV	0.5-200Hz
Galvanic Skin Response (GSR)	Skin	Measurement of conductance (output measured in mV, depends on sensor)	0.01-1Hz

1.3.1 Electrocardiogram

Electrocardiogram (ECG) is recording of the heart's electrical activity. It is a quasi-periodic, rhythmically repeating signal that reflects the heart's synchronized bioelectric events, functioning as a natural generator of these signals. The heart possesses its own mechanism for generating and transmitting action potentials through intricate changes in ionic concentrations across cell membranes. Positioned in the upper right atrium at the entry of the vena cava is a cluster of cells known as the sinoatrial (SA) node. This node serves as the heart's primary pacemaker, initiating its activity.

To diagnose heart diseases, various wave patterns from an ECG signal—like P, Q, R, S, and T waves—provide critical insights into heart function. These patterns include prominent peaks and valleys that represent different phases of cardiac activity. Normal human ECG signals have a frequency range of 0.05–120 Hz and low amplitudes in the millivolt range [5].

The **P wave** represents atrial depolarization, with a duration of less than 0.11 seconds and an amplitude of up to 0.25 mV. The **QRS complex** is the most commonly analyzed feature for diagnosing heart diseases, representing ventricular depolarization. Its duration typically ranges from 0.08 to 0.10 seconds. Within this complex:

- The **Q wave** is the first negative deflection, with an amplitude about 25% of the **R wave**.
- The **R wave** is the main positive peak, with an amplitude of approximately 1.60 mV.
- The **S wave** is the final negative deflection.

The **T wave** signifies ventricular repolarization, with an amplitude between 0.1 and 0.5 mV. The **PR interval** measures the time from the onset of atrial depolarization to the start of ventricular depolarization, including atrioventricular nodal delay, with a duration of 0.12 to 0.20 seconds. The **QT interval** reflects the combined duration of ventricular depolarization and repolarization, lasting between 0.20 and 0.40 seconds. Finally, the **ST segment** represents the isoelectric period when the ventricles are fully depolarized [5]. Figure 1.2 shows a typical ECG waveform generated by heart.

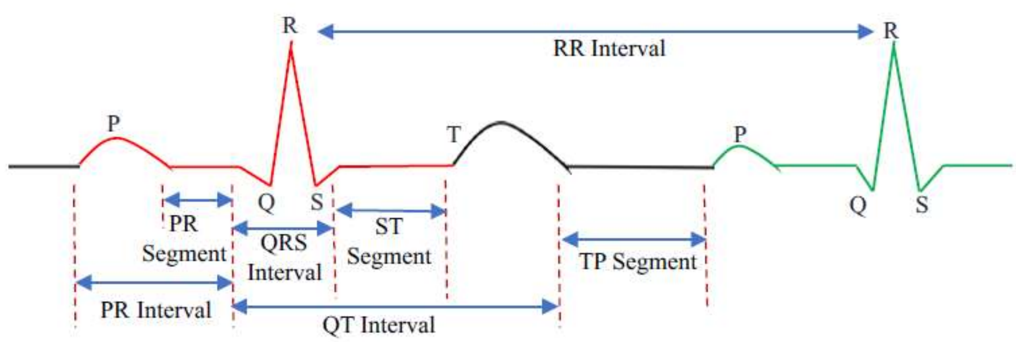


Figure 1.2 A typical ECG Waveform [5].

The first ECG machine was invented by Willem Einthoven, who made significant contributions through his pioneering work [6]. In 1908, he published a detailed description of the first clinically viable ECG measurement system. The term "Einthoven’s triangle" honors him and refers to an imaginary inverted equilateral triangle centered on the chest, with its vertices corresponding to the standard electrode placements on the arms and leg.

Frank Norman Wilson later introduced a novel approach for defining electrocardiographic unipolar potentials. He proposed using the central terminal (CT) as a reference point, a method still widely utilized today [6]. Unipolar potentials are derived by connecting resistors from each terminal of the limb leads to a common point—the central terminal, as illustrated in Figure 1.3. These potentials are measured relative to this central terminal. The Wilson central terminal represents the average of the limb potentials, as the total current flowing into it from the limb leads must sum to zero, adhering to Kirchhoff's First Law. This law states that the algebraic sum of currents at a junction in a network of conductors equals zero (IR + IL + IF = 0) [6]. Where IR represents current flows through right arm, IL represents current flows through left arm and IF represents current flows through left foot.

The resistance value of each terminal plays a crucial role, and fortunately, modern biopotential amplifiers (Instrumentation Amplifiers) have high input impedance, which enhances the Common-Mode Rejection Ratio (CMRR). In Figure 1.3, within the context of the Einthoven triangle, the bipolar limb leads—designated as I, II, and III—are also shown. These leads track the electrical potential of the heart when three electrodes are placed on the right and left hands and the left foot.

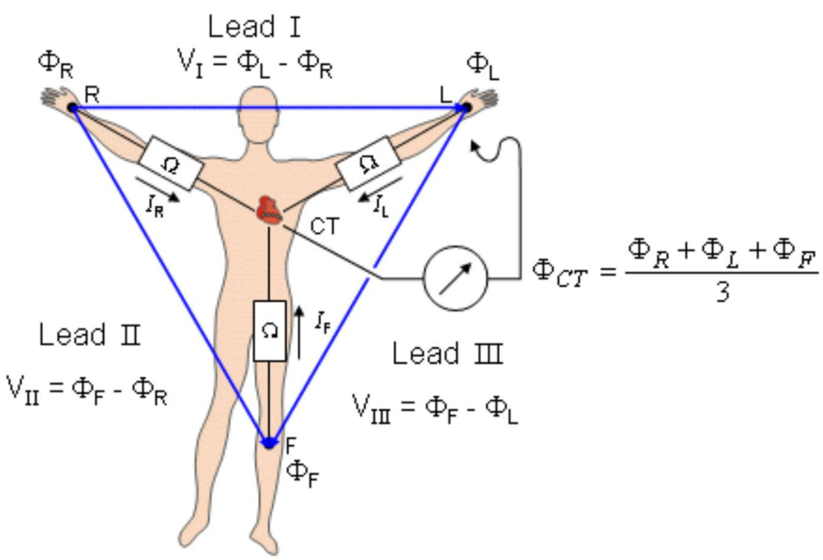


Figure 1.3 Wilson Central Terminal [6].

The voltages and potentials are described below:

- V_I = Lead I voltage;
- V_{II} = Lead II voltage;
- V_{III} = Lead III voltage;
- ϕ_L = Left hand potential;
- ϕ_R = Right hand potential;
- ϕ_F = Left foot potential.

Other category of lead orientation is the precordial leads (V1, V2, V3, V4, V5, V6), which are recorded using six additional electrodes placed on the chest. These leads provide more detailed information within the ECG, as shown in Figure 1.4.

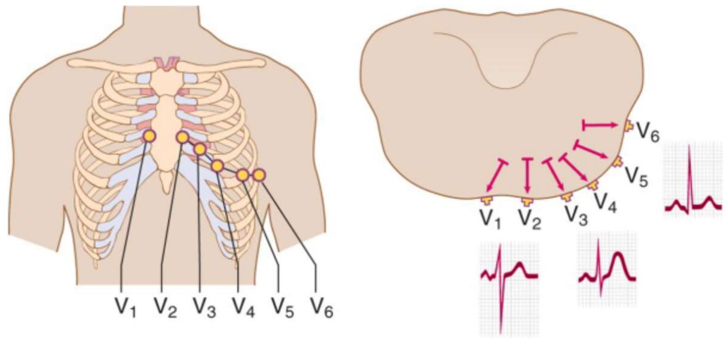


Figure 1.4 Precordial leads [7].

1.3.1.1 Significance of ECG Waveform

The Electrocardiogram (ECG) waveform is a critical tool in the field of medical diagnostics and research. Its significance lies in its ability to provide a detailed representation of the electrical activity of the heart, offering valuable insights into its structure, function, and overall health. Below are the key points highlighting the importance of the ECG waveform:

(i) Diagnosis of Cardiac Disorders

The ECG waveform enables the identification of a wide range of heart conditions, such as arrhythmias, ischemia, myocardial infarction, and heart block.

Abnormalities in wave patterns, intervals, or segments can indicate specific pathological conditions, aiding in timely diagnosis and intervention.

(ii) Evaluation of Heart Function

The waveform components (P, Q, R, S, and T waves) provide information on the depolarization and repolarization processes of the atria and ventricles, reflecting how effectively the heart is pumping blood.

Parameters like heart rate, rhythm, and conduction velocity can be assessed from the ECG.

(iii) Monitoring of Therapeutic Interventions

ECG is essential for monitoring the effectiveness of treatments, such as medications, pacemaker functionality, or post-surgical cardiac rehabilitation.

It is also used during and after procedures like angioplasty and cardiac ablation to assess heart activity.

(iv) Detection of Silent Cardiac Events

The ECG can detect silent myocardial infarctions or ischemic episodes that may not present with noticeable symptoms, providing a preventive diagnostic measure.

(v) Assessment of Electrolyte Imbalances

Changes in the ECG waveform, such as alterations in the QT interval, can indicate imbalances in potassium, calcium, and other electrolytes that are critical for cardiac function.

(vi) Non-Invasive Nature

As a non-invasive diagnostic tool, the ECG is safe, quick, and cost-effective, making it suitable for routine screening and emergency evaluations.

(vii) Utility in Exercise and Stress Testing

During exercise or stress tests, ECG waveforms help assess the heart's response to physical activity, identifying conditions like stress-induced ischemia.

(viii) Research and Development

ECG waveforms are integral to studying cardiac physiology and the effects of new drugs or therapies on heart function.

(ix) Screening for Congenital and Genetic Disorders

Certain congenital heart defects and inherited conditions like Long QT Syndrome or Brugada Syndrome can be detected through characteristic ECG abnormalities.

(xi) Evaluation of Heart Rate Variability (HRV)

ECG data are used to analyze HRV, which is a marker of autonomic nervous system balance and overall cardiovascular health.

The ECG waveform is indispensable for cardiology and general medicine. Its ability to provide real-time, actionable insights into cardiac health makes it a cornerstone in both preventive and curative healthcare practices.

1.3.2 Electroencephalogram

Electroencephalogram (EEG) is a diagnostic technique that records the electrical activity of the brain captured through electrodes placed on the scalp. This method is widely used in neuroscience, medicine, and psychology to study brain function and diagnose neurological disorders. EEG signals originate from the electrical activity of neurons, particularly postsynaptic potentials generated by the synchronized activity of pyramidal neurons in the cerebral cortex. These signals are of very low amplitude, typically in the range of 5–300 μV, and have frequencies ranging from 0.1 Hz to 150 Hz or higher. EEG is a completely non-invasive procedure, making it suitable for repeated use without risk to the patient.

EEG signals consist of rhythmic patterns classified based on their frequency ranges [3] and shown in figure 1.5:

- *Delta Waves (0.5–4 Hz):* Associated with deep sleep and restorative processes.
- *Theta Waves (4–8 Hz):* Linked to drowsiness, light sleep, and meditative states.
- *Alpha Waves (8–13 Hz):* Observed during relaxed, awake states, often with eyes closed.
- *Beta Waves (13–30 Hz):* Related to active thinking, focus, and problem-solving.
- *Gamma Waves (30–100 Hz):* Involved in high-level cognitive functioning and consciousness.

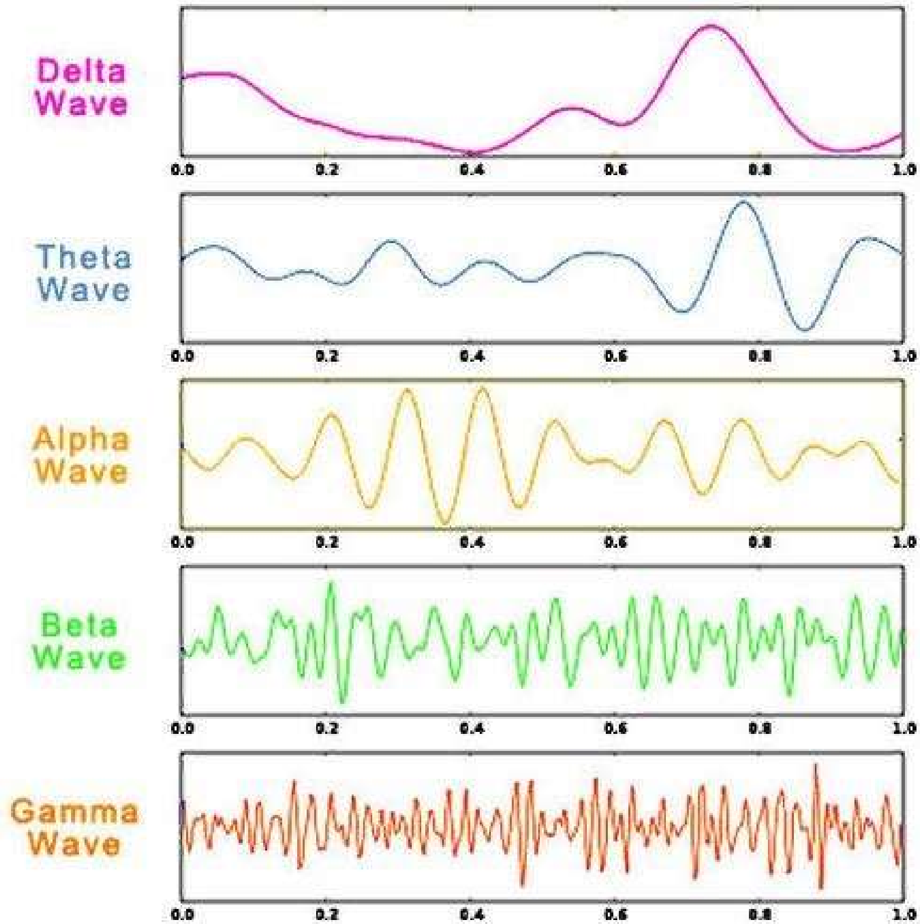


Figure 1.5 Typical EEG Waveforms

1.3.2.1 Significance of EEG Waveform

EEG waveforms hold immense clinical and research value as they provide direct insights into the electrical activity of the brain. These waveforms, characterized by their frequency, amplitude, and morphology, are significant in understanding various brain functions, diagnosing neurological conditions, and studying cognitive processes. Below are the key aspects of their significance:

(i) ***Neurological Disorders****:* EEG waveforms are critical in detecting abnormalities such as epilepsy, seizures, and focal brain disorders. For example, spikes and sharp waves are indicative of epileptic activity.

(ii) ***Brain Injuries:*** EEG is used to assess brain function following trauma, strokes, or hypoxic-ischemic injuries.

(iii) ***Sleep Disorders:*** Waveforms like delta and theta waves are analyzed during sleep studies to diagnose conditions like insomnia, sleep apnea, and narcolepsy.

(iv) ***Learning and Memory:*** EEG activity patterns provide clues about memory formation and learning processes, particularly involving theta rhythms.

(v) ***Coma and Vegetative States:*** EEG is used to evaluate brain function in patients with altered consciousness, helping to differentiate between comatose, vegetative, and minimally conscious states.

(vi) ***Surgical and ICU Monitoring:*** Real-time EEG monitoring helps assess the brain's response during surgeries or in critically ill patients to detect seizures or brain hypoxia.

(vii) ***Neurofeedback:*** EEG waveforms are used in biofeedback therapies, where patients learn to modulate brain activity, aiding in conditions like anxiety, ADHD (Attention-Deficit/Hyperactivity Disorder), and depression.

(viii) ***Brain-Computer Interfaces (BCI):*** EEG waveforms enable communication and control in assistive technologies for individuals with motor impairments.

(ix) ***Brain Connectivity Studies:*** EEG waveforms are used to analyze connectivity and synchronization between different brain regions, aiding in understanding neural network dynamics.

(x) ***Developmental Studies:*** EEG helps track brain development in infants and children, providing insights into conditions like autism and developmental delays.

1.3.3 Electromyogram

The contraction of skeletal muscles generates action potentials within individual muscle fibers, which are recorded as an electromyogram (EMG). While similar to the activity observed in cardiac muscles, skeletal muscle repolarization occurs significantly faster, with action potentials lasting only a few milliseconds. EMG measurements typically focus on assessing the overall activity of a specific muscle or group of muscles, rather than individual muscle fibers. As a result, the EMG pattern represents the summation of action potentials from multiple fibers within the muscle or muscles under study [3].

It measures action potentials generated during muscle contraction and relaxation, offering valuable data for diagnosing neuromuscular disorders, analyzing movement, and designing rehabilitation protocols. As shown in Figure 1.6, when the Central Nervous System (CNS) activates a muscle via motor neurons (which control body movements and many bodily functions), muscle fiber contraction occurs following the depolarization of the outer muscle-fiber membrane. The depolarized zones of the fibers within each recruited Motor Unit (MU) generate an electrical field, creating voltage contributions that sum up on the skin to form a voltage distribution [9]. This summation is influenced by the distance of each source from the skin.

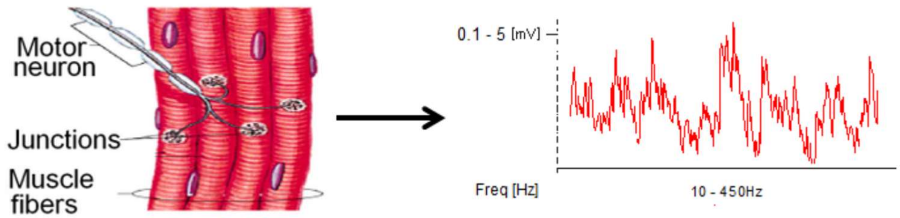


Figure 1.6 Electrophysiology of the muscles [8].

EMG signals are captured through electrodes placed on the skin (surface EMG) or by inserting electrodes into the muscle (intramuscular EMG). By placing electrodes on the skin, the voltage at specific points in the surrounding area can be measured. Typically, two electrodes are used per muscle as shown in Figure 1.7, and the difference between the two cutaneous potentials is recorded [10]. When surface electrodes are positioned on the skin parallel to the muscle fibers, the traveling potential generated by muscle activation is detected by the electrodes. This detection includes a temporal delay that is directly influenced by the conduction velocity of the muscle fibers.

These signals, which typically range in amplitude from 0.1 mV to 5 mV and frequencies between 0.1 Hz and 1000 Hz, are amplified and analyzed to assess muscle activation patterns, detect abnormalities, and evaluate fatigue. The technique is widely applied in clinical diagnostics, sports science, prosthetics, and ergonomics, making it a critical tool for understanding and improving muscular and neuromuscular performance. A typical EMG waveform is shown in figure 1.8.

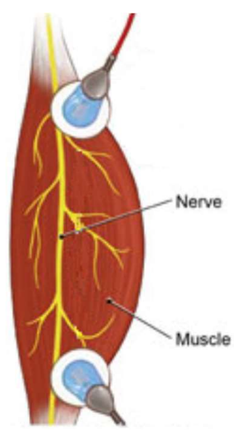


Figure 1.7 EMG Electrode placement [11].

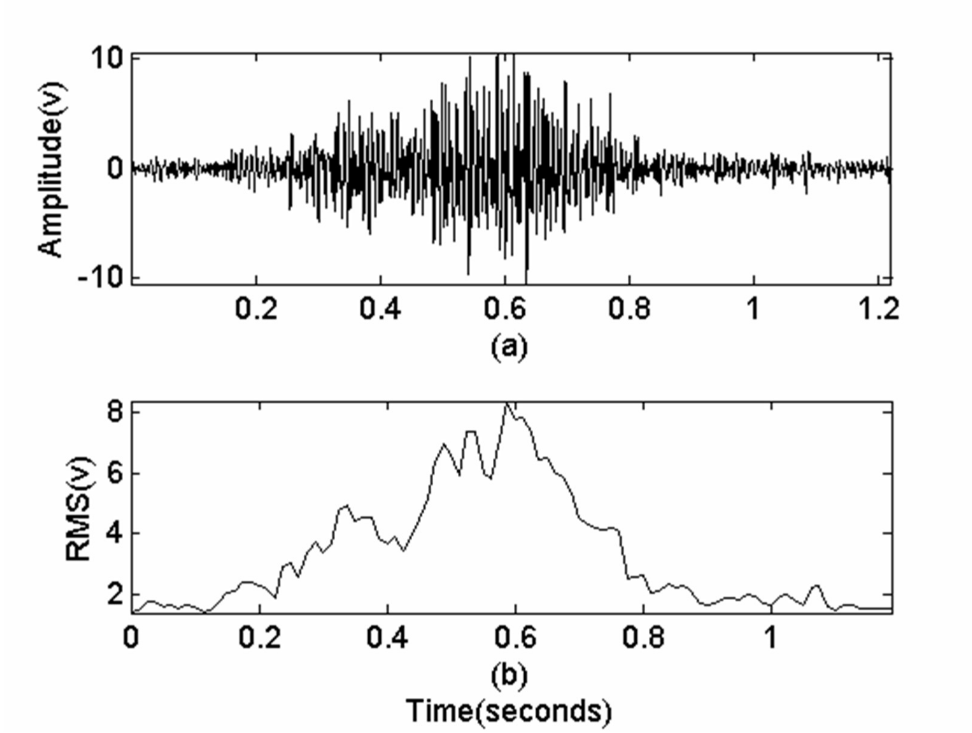


Figure 1.8 A typical EMG Waveform in time domain

1.3.3.1 Significance of EMG Waveform

(i) ***Assessment of Muscle Function:*** EMG waveforms provide critical information about the functionality and activation of skeletal muscles during voluntary or involuntary contractions. They help assess the coordination and strength of muscle groups.

(ii) ***Diagnosis of Neuromuscular Disorders:*** EMG waveforms are used to identify and diagnose neuromuscular disorders such as muscular dystrophy, myopathies, peripheral neuropathies, and motor neuron diseases. Abnormalities in waveform patterns, such as prolonged duration or reduced amplitude, may indicate underlying pathology.

(iii) ***Rehabilitation and Therapy Monitoring:*** EMG signals are widely used in physical therapy and rehabilitation to monitor muscle recovery and guide therapy for patients with injuries or post-surgery conditions. Biofeedback techniques use EMG waveforms to train patients in controlling muscle activity.

(iv) ***Ergonomics and Biomechanics:*** EMG studies help analyze muscle fatigue, posture, and workload during various physical activities, providing insights into ergonomics and injury prevention. It aids in the design of tools, workspaces, and athletic training programs.

(v) ***Research in Motor Control:*** EMG signals contribute to understanding how the nervous system controls muscle movement and coordination. It is used in studies of motor learning and adaptation in response to different stimuli or environments.

(vi) ***Prosthetics and Assistive Devices:*** EMG signals are employed in controlling prosthetic limbs and assistive devices, enabling natural and intuitive movement for amputees or individuals with disabilities.

(vii) ***Evaluation of Muscle Fatigue:*** Changes in EMG waveform frequency and amplitude help assess muscle fatigue during sustained or repetitive activities. This is valuable in sports science and occupational health.

(viii) ***Signal Characterization:*** The analysis of EMG waveform parameters, such as amplitude, frequency, and duration, provides detailed insights into muscle contraction intensity and recruitment patterns.

1.3.4 Electrooculogram

An electrooculogram (EOG) is a biopotential signal that records the electrical activity associated with eye movements. This signal is generated by the corneo-retinal potential, which exists due to the difference in electrical charges between the cornea (positive) and the retina (negative). Electrodes placed around the eyes capture this potential as the eyes move, enabling the measurement of horizontal and vertical eye movements. The EOG is widely used in clinical and research applications. Clinically, it aids in diagnosing retinal and eye movement disorders, such as Best's disease and oculomotor dysfunctions. Beyond medicine, EOG signals are used in assistive technologies, such as eye-controlled communication systems and human-computer interfaces, providing valuable solutions for individuals with physical disabilities. The ability of the EOG to monitor gaze direction, blinking patterns, and eye movement dynamics makes it a versatile tool in fields ranging from neurology to user interaction design. A typical EMG waveform is shown in figure 1.9.

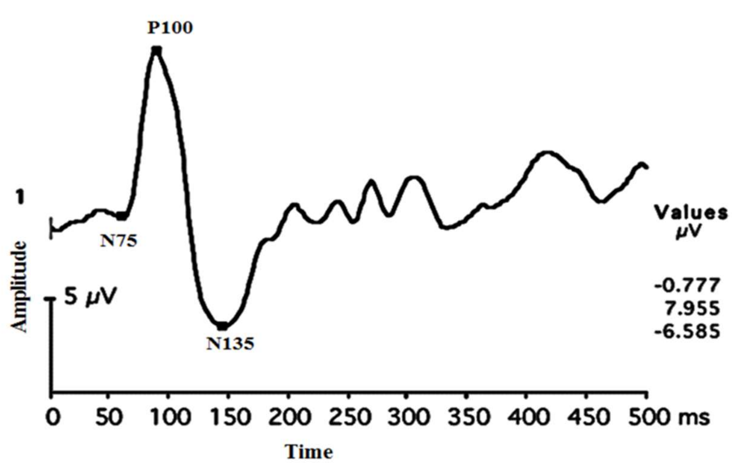


Figure 1.9 A typical EOG Waveform

1.3.4.1 Significance of EOG Waveform

The electrooculogram (EOG) waveform holds significant importance in both clinical diagnostics and advanced technological applications. Its primary significance lies in its ability to monitor eye movements and detect gaze direction, making it an essential tool for diagnosing disorders such as retinitis pigmentosa, Best's disease, and other oculomotor dysfunctions. The EOG waveform provides insights into the function of the retinal pigment epithelium and eye muscle coordination, enabling early detection of abnormalities.

In addition to clinical applications, the EOG waveform is crucial in assistive technology and human-computer interaction. It enables eye-controlled systems for individuals with motor impairments, allowing them to communicate or control devices using eye movements. The waveform is also utilized in sleep studies, driver fatigue monitoring, and research on visual attention and cognitive load. By analyzing the amplitude and direction of the EOG waveform, researchers and clinicians gain valuable information about visual and neurological functions, making it a versatile and impactful tool in medicine and technology.

1.3.5 Electrocorticogram

An electrocorticogram (ECoG) is a diagnostic technique that records the electrical activity directly from the surface of the brain, typically by placing electrodes on the exposed cortical surface during neurosurgical procedures. It is an invasive procedure, unlike non-invasive methods such as electroencephalogram (EEG), which records brain activity from the scalp. ECoG is primarily used in both clinical and research settings to gain deeper insights into brain function, particularly in patients undergoing surgery for epilepsy, brain tumors, or other neurological conditions.

The ECoG technique involves the implantation of electrodes either temporarily or permanently onto the dura mater (the outermost layer of the meninges) or directly onto the cerebral cortex. These electrodes can be placed in a grid or strip configuration, depending on the clinical needs and the location of the brain region being monitored. During an ECoG recording, the electrodes detect electrical activity from neurons, which are then amplified and recorded for analysis.

Because the electrodes are placed directly on the cortical surface, the signal obtained via ECoG is much higher in spatial resolution compared to EEG, which measures activity from the scalp and therefore includes a lot more interference from other tissues. The data recorded from ECoG provides a more detailed and localized picture of brain activity, making it particularly useful for mapping brain regions responsible for specific functions such as motor control, sensory processing, and speech. A typical ECoG waveform is shown in figure 1.10.

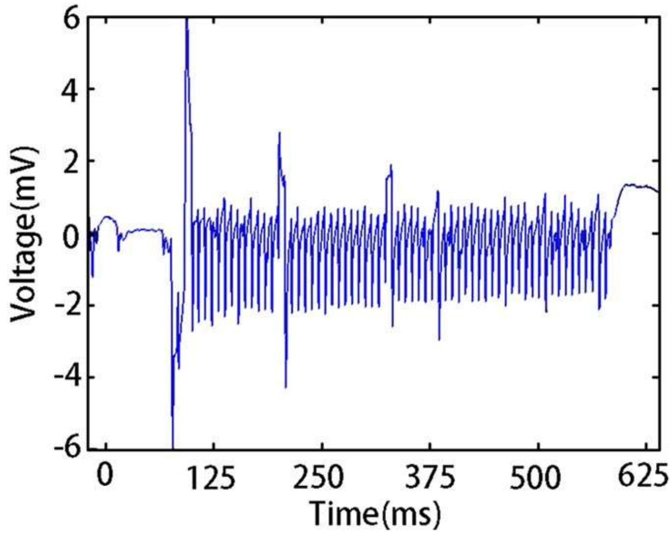


Figure 1.10 A typical ECoG Waveform

1.3.5.1 Significance of ECoG Waveform

ECoG waveforms hold immense significance in both clinical and research contexts, offering detailed insights into the functionality and health of the brain. Understanding and interpreting ECoG waveforms are crucial for diagnosing neurological disorders, planning surgeries, and advancing neuroscience.

(i) ***High Spatial Resolution:*** ECoG provides waveforms with a much higher spatial resolution compared to non-invasive techniques like EEG. The localized nature of the waveform allows clinicians to identify the precise regions of the brain responsible for abnormal or normal activity, which is especially important in conditions like epilepsy.

(ii) ***Epileptic Seizure Detection:*** In patients with epilepsy, ECoG waveforms are critical for identifying seizure foci. Abnormal waveforms, such as sharp waves, spikes, or rhythmic discharges, indicate regions of the brain generating epileptic activity. This information aids in targeted surgical interventions to remove or isolate the affected brain tissue.

(iii) ***Functional Mapping:*** ECoG waveforms are used to map motor, sensory, and language areas of the brain during neurosurgery. By analyzing changes in waveform patterns in response to specific stimuli or tasks, surgeons can identify and preserve essential cortical areas while removing pathological regions.

(iv) ***Brain-Computer Interfaces (BCI):*** ECoG waveforms form the foundation for advanced brain-computer interfaces. The precise recording of neural activity from ECoG allows users to control external devices like prosthetic limbs or communication systems, enabling significant advancements in assistive technologies for individuals with disabilities.

(v) ***Detection of Pathophysiological States:*** ECoG waveforms can indicate various neurological conditions beyond epilepsy, such as brain tumors, traumatic brain injuries, and stroke-related changes. Deviations in normal waveform patterns help in diagnosing and monitoring these conditions.

(vi) ***Advancements in Neuroscience Research:*** ECoG waveforms are invaluable in understanding how different brain regions communicate and process information. High-frequency activity captured in ECoG (e.g., gamma oscillations) provides insights into complex cognitive processes like memory encoding, decision-making, and sensory integration.

1.3.6 Galvanic Skin Response

The Galvanic Skin Response (GSR), also known as Electrodermal Activity (EDA), refers to changes in the electrical properties of the skin due to variations in sweat gland activity, which are controlled by the autonomic nervous system (ANS). It is a physiological marker of emotional arousal and has been widely used in psychology, neuroscience, and psychophysiological research to assess emotional and stress responses.

The GSR is based on the principle that the skin's electrical conductivity increases with higher levels of perspiration. Sweat glands, primarily located on the palms of the hands and soles of the feet, are activated by the sympathetic nervous system in response to emotional or physiological arousal. This leads to an increase in skin moisture, which reduces the skin's resistance and enhances its ability to conduct electricity. Two electrodes are typically placed on the skin to measure this conductivity, with the resulting data reflecting changes in arousal states.

GSR has two components.

(i) ***Tonic Component:*** It refers to the baseline level of skin conductivity, which varies between individuals and is influenced by factors such as hydration, skin condition, and environmental temperature. The tonic level provides a general measure of the individual's physiological state over time.

(ii) ***Phasic Component:*** It refers to rapid, temporary changes in skin conductivity due to specific stimuli or events. These changes are known as Skin Conductance Responses (SCRs) and are often associated with emotional reactions, attention shifts, or cognitive processing.

Electrodermal activity (EDA) is commonly measured at the palmar surfaces of the hands or feet, where the density of sweat glands exceeds 2000/cm^2. This method, illustrated in Figure 1.11, follows the approach proposed by Venables and Christie (1980) [12]. A typical mean GSR waveform is shown in figure 1.12.

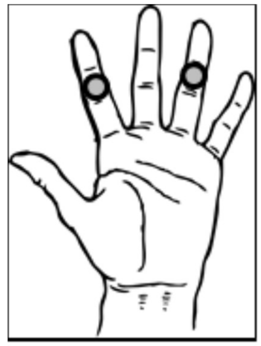


Figure 1.11 Recommended electrode placement for GSR measurement.

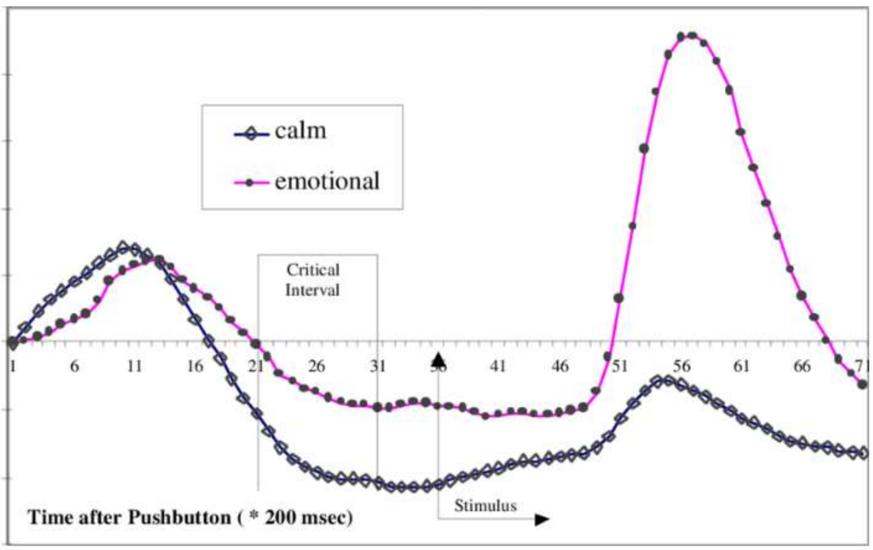


Figure 1.12 The Mean Galvanic Skin Response (GSR) is plotted against the sample number (time) for two stimulus categories: calm and emotional, with stimulus presentation beginning at sample 37.. The critical interval where the response P was hypothesized to occur is also indicated [13]

1.3.6.1 Significance of GSR

The significance of GSR lies in its ability to provide real-time, emotional and physiological state of an individual, making it a valuable tool across various fields of research, clinical practice, and applied sciences.

(i) ***Indicator of Emotional Arousal:*** GSR is a reliable measure of sympathetic nervous system activity, which governs the body's fight-or-flight responses. It serves as an indicator of emotional states such as stress, fear, excitement, or surprise, making it critical for studying human emotions.

(ii) ***Real-Time Monitoring:*** GSR provides immediate feedback on physiological responses to stimuli, enabling the dynamic study of how individuals react to specific events or environments. This feature is especially useful in research on stress, decision-making, and user experience.

(iii) ***Applications in Psychophysiological Research:*** Researchers use GSR to study the physiological basis of emotions, attention, and cognitive processes. It bridges the gap between observable behaviors and underlying neural mechanisms, offering insights into the mind-body connection.

(iv) ***Clinical Relevance:*** GSR is utilized in biofeedback therapy to help patients manage stress, anxiety, and other psychological conditions. It is also explored for diagnosing and monitoring disorders such as PTSD (Post-traumatic stress disorder), phobias, and depression by assessing autonomic nervous system dysfunction.

(v) ***Polygraph Testing:*** GSR is a core component of lie detection tests, where changes in skin conductance are measured to detect stress or arousal associated with deception.

(vi) ***Human-Computer Interaction (HCI):*** GSR is used to evaluate user engagement and stress levels during interactions with technology, such as virtual reality systems, games, and user interfaces. This helps in designing more intuitive and user-friendly systems.

(vii) ***Market Research and Advertising:*** In marketing, GSR is employed to measure consumer emotional engagement with advertisements, products, or experiences. By analyzing arousal patterns, businesses can tailor campaigns to resonate better with their target audiences.

(viii) ***Cognitive Load and Decision-Making:*** GSR provides valuable insights into cognitive processes by correlating physiological arousal with decision-making and problem-solving tasks. It helps researchers understand how individuals allocate attention and resources under varying levels of difficulty or pressure.

(ix) ***Advancements in Wearable Technology:*** Modern wearable devices equipped with GSR sensors enable continuous monitoring of emotional states, making it easier to track stress and arousal in daily life. This has applications in fitness, mental health management, and personal productivity.

1.4 Biopotential Data Acquisition System

Biopotential data acquisition system (Bio DAQ) is a specialized tool, utilized in medical and research domains to capture and amplify the body's electrical signals. These systems play a crucial role in obtaining precise and high-quality data from various physiological sources. These systems are integral in biomedical applications, capturing signals such as electrocardiograms (ECG), electroencephalograms (EEG), and electromyograms (EMG). The process begins with specialized sensors or electrodes that detect biopotential signals from the skin or underlying tissues. These weak signals, typically in the microvolt to millivolt range, are then amplified using precision amplifiers to ensure they are strong enough for analysis. Noise filtering mechanisms are applied to eliminate interference from environmental and physiological artifacts, ensuring signal clarity. The filtered signals are converted into digital form using Analog-to-Digital Converters (ADCs), enabling further processing and storage. Modern biopotential data acquisition systems often integrate wireless communication, real-time monitoring capabilities, and advanced signal processing algorithms to enhance diagnostic accuracy and enable remote healthcare applications. These systems play a critical role in medical diagnostics, patient monitoring, and research in neurophysiology and cardiology.

1.5 Challenges in Designing a Biopotential Data Acquisition System

(i) ***Signal Noise and Artifacts:*** Biopotential signals are inherently weak and susceptible to noise from external sources such as electromagnetic interference and motion artifacts. These interferences can degrade signal quality, making accurate analysis challenging.

(ii) ***Electrode-Skin Impedance:*** Maintaining consistent contact between the electrodes and the skin is critical. Variations in skin impedance due to sweat, movement, or improper placement can distort the signal, leading to unreliable readings.

(iii) ***Power Consumption:*** Portable and wearable systems demand efficient power management to ensure prolonged operation. Balancing low power consumption with high-quality signal acquisition remains a significant design challenge.

(iv) ***Data Volume and Processing:*** Continuous monitoring generates large volumes of data, requiring robust storage and processing capabilities. Efficient algorithms are needed to manage, analyze, and interpret this data in real time without latency.

(v) ***User Comfort:*** Wearable devices or electrode setups often compromise user comfort, especially in long-term monitoring scenarios. Bulky designs, adhesive irritation, and limited mobility hinder patient compliance.

(vi) ***Cost and Accessibility:*** High-quality acquisition systems often involve expensive components, which can limit their accessibility for widespread clinical and research use, particularly in low-resource settings.

(vii) ***Standardization and Compatibility:*** Lack of universal standards across devices and platforms can lead to interoperability issues, making it difficult to integrate data from different systems or manufacturers.

(viii) ***Environmental Sensitivity:*** Factors such as temperature, humidity, and physical activity can influence signal acquisition, necessitating systems capable of adapting to varying environmental conditions.

(ix) ***Limited Diagnostic Accuracy:*** Despite advancements, false positives or negatives in signal interpretation still occur, leading to potential misdiagnosis or missed health events.

(x) ***Regulatory and Privacy Concerns:*** The acquisition and transmission of biopotential data pose significant privacy risks. Ensuring compliance with data protection regulations while maintaining system security is a persistent challenge

Addressing these limitations requires multidisciplinary efforts, integrating advances in materials science, electronics, signal processing, and data analytics to optimize system performance and expand their clinical and research applications.

1.6 Limitations in Current Biopotential Data Acquisition Systems

Different biopotential data acquisition (Bio DAQ) systems are available in market, most of which are designed for specific signals like EMG, ECG, EEG etc and mostly are the wired systems. An analysis of the available multi-channel systems available in the market commercially is described in Table 1.2. Detail analysis of different work and previous studies are illustrated in chapter 2. The systems are classified based on nos of channels, wireless connectivity, availability of integrated stimulator, approximate cost etc.

Table 1.2 Review of current devices available in market

Name of Manufacturer	**Nos of Channel**	**Wireless Data Transfer**	**Integrated Stimulator**	**Approx Cost (INR)**	**Remarks**
A D Instruments (Australia))	16	No	No	Rs. 14-15 Lakh	Not portable
iWorks Systems (USA)	16	No(Single parameter wireless module available)	No (standalone trigger available)	Rs. 8-10 Lakh	Not portable
Nexus (Scotland)	10	Yes	No	Rs. 10-15 Lakh	Portable
Medicaid (India)	16	No	No	Rs. 5-6 Lakh	Not portable
Tmsi (Netherlands)	16	Yes	No	Rs. 14-15 Lakh	Portable

The limitations of the current available systems are described below:

(i) ***Signal specific****:* Most commercially available systems are tailored for specific signals such as ECG, EMG, or EEG. The amplifier gains and filter frequencies in these systems are optimized for the targeted signals, making it challenging to use a single device for acquiring other types of signals. For example, the device and amplifier is specifically designed for acquiring ECG signals cannot be used for acquiring EMG signals. This restricts the versatility of the system.

(ii) ***Lack of wireless connectivity and User comfort****:* Majority of the systems available in the market are wired systems. Wired systems have different limitations. It is very uncomfortable for the subjects due to complexity of wires. Their free activities and movements have been restricted especially in long-term monitoring scenarios. Several times, in between experiments, some electrodes got removed and data not been able to record properly. Sometimes lead wires while passing through some power cables, introduced noise.

(iii) ***Non-availability of integrated stimulator**:* An integrated stimulator allows controlled delivery of stimuli (e.g., electrical pulse) to evoke physiological responses. This capability is critical for diagnostic applications such as nerve conduction studies and evoked potential testing, where analyzing the body's response to stimuli helps identify abnormalities. Most of the systems available in the market do not have integrated stimulator. Integrated stimulator has several advantages mentioned below:

(a) *Closed-Loop Systems:* With an integrated stimulator, Bio DAQ systems can operate in a closed-loop configuration, where the system adjusts stimulation parameters in real-time based on the monitored physiological signals. This is particularly beneficial in therapeutic applications such as neuro-stimulation or biofeedback.

(b) *Simplified Experimental Setup:* Combining the stimulator and acquisition modules in a single device reduces the need for multiple external instruments, simplifying the setup for clinical and research use. This integration minimizes wiring, reduces signal interference, and enhances portability.

(c) *Improved Signal Quality:* The proximity of the stimulator to the data acquisition unit ensures synchronized operation and reduces the latency and noise that might occur when using separate devices. This synchronization enhances the reliability and precision of stimulus-response measurements.

(d) *Versatility in Applications:* Integrated stimulators expand the functionality of biopotential systems, enabling their use in diverse applications such as rehabilitation, neuromodulation, sensory studies, and brain-computer interfaces (BCIs).

(e) *Time and Cost Efficiency:* By eliminating the need for separate stimulators, integrated systems reduce equipment costs and streamline workflows. Researchers and clinicians can perform stimulation and data acquisition simultaneously without requiring additional coordination.

(f) *Enhanced Portability and Wearability:* In wearable or compact designs, integration reduces the overall size and weight of the system, making it more practical for mobile or long-term monitoring applications.

(g) *Customizable Protocols:* Integrated systems with programmable stimulators, enabling users to design and execute customized stimulation protocols tailored to specific research or therapeutic needs.

(h) *Reduced Signal Drift:* The integration minimizes physical and electrical separation between stimulation and acquisition components, reducing artifacts and drift in the acquired biopotential signals.

(i) *Scalability and Future Applications:* Integrated stimulators pave the way for advancements in real-time therapies, such as adaptive stimulation for epilepsy, functional electrical stimulation (FES), pain management, or motor recovery, where immediate adjustments are crucial for effective treatment.

(iv) ***Portability****:* Most of the systems available in the market are not portable. Bulky designs, adhesive irritation, and limited mobility hinder patient compliance.

(v) ***Animal studies:*** Most of the systems available in the market are designed for human use only and not suitable for animal studies. Animal studies require compact portable devices with wireless transmission of signals, so that it does not create any hindrance in their normal behavior.

1.7 Motivation

The motivation to develop a wireless biopotential data acquisition system with an integrated stimulator stems from the growing demand for advanced, user-friendly, and multifunctional biomedical devices. Traditional wired systems often face challenges such as limited mobility, discomfort during long-term use, and susceptibility to signal artifacts caused by tangled or disconnected cables. These are also not suitable for animal studies. By transitioning to wireless technology, these limitations are addressed, enabling greater freedom of movement for patients and participants, which is crucial in applications such as remote monitoring, rehabilitation, and sports science.

Wireless systems also facilitate seamless data transmission to cloud platforms or nearby devices, enabling real-time analysis, remote supervision by clinicians, and integration with telemedicine platforms. Moreover, the compact and portable nature of these systems makes them ideal for in-home or field settings, reducing the dependency on hospital-based care.

Most commercially available systems are tailored for specific signals such as ECG, EEG, or EMG. The amplifier gains and filter frequencies in these systems are optimized for the targeted signals, making it challenging to use a single device for acquiring other types of signals. For example, the device and amplifier is specifically designed for acquiring ECG signals cannot be used for acquiring EMG signals. This restricts the versatility of the system.

To address this challenge, we have developed an innovative hardware filters along with user-configurable digital filters for each channel, with specific signal frequencies such as EMG, ECG, EEG, and EOG. This flexibility allows the same system to simultaneously acquire multiple signals, such as ECG alongside EMG or EOG, ensuring versatility in various applications.

Integrating a stimulator further enhances the system's utility by allowing precise delivery of controlled stimuli while simultaneously recording the body's physiological responses. This dual functionality is especially beneficial for applications such as neuro-stimulation, cardiac pacing, and closed-loop therapeutic systems, where real-time interaction between stimulation and response is essential.

This system can be used as a therapeutic device as well as for research purposes. Physiological data before applying the stimulus pulse and after applying the stimulus pulse can be recorded and studied. It will be useful for animal experiments also. The device can be attached to any animal, allowing for remote monitoring of physiological parameters as well as the impact of the applied stimulus.

Most commercially available stimulators are developed using oscillator circuits and transformers, which fail to generate properly charge-balanced pulses. Such waveforms can result in tissue damage due to the continuous flow of direct current. When an electrode transmits current through a conductive solution, chemical reactions occur at the interface. Prolonged application of high voltage can induce strong faradic currents, leading to gas formation, electrolysis, pH shifts, electrode corrosion, and tissue damage [14, 15]. Ensuring properly charge-balanced waveforms is essential to prevent these adverse effects and maintain patient safety over extended use is a major challenge.

To address this challenge, we have developed an innovative integrated stimulator which produce microcontroller-based charge-balanced waveform of trapezoidal shape into our stimulator design. Trapezoidal wave patterns, which ramp up and down gradually, are particularly effective in providing comfortable and strong muscle stimulation while avoiding sudden, uncomfortable responses [16]. Additionally, the stimulator features an adjustable frequency and pulse width, which can be modified using a controllable knob. This allows users to fine-tune the parameters according to their specific needs, enhancing the device's versatility and adaptability for various applications.

The combination of wireless communication, versatile user selectable signal filters and an integrated stimulator fosters innovation in personalized medicine, allowing customizable protocols tailored to individual needs while ensuring patient comfort and compliance. By combining stimulation and acquisition capabilities, these systems provide a comprehensive platform for advanced diagnostics, therapy, and research, promoting innovation in biomedical engineering and healthcare, with the broader goals of improving healthcare accessibility, reducing costs, and enhancing diagnostic and therapeutic outcomes.

1.8 Thesis Objectives

The overall aim of this thesis is to develop and evaluate a wireless, low-cost, compact, 16 - channel Biopotential Data Acquisition (Bio DAQ), and integrated arbitrary waveform stimulator system. This involves developing a compact, low-power, portable wireless module that can be attached to the human body to accurately sense, amplify, and transmit biological signals ranging from tens of microvolts to several millivolts. Additionally, it includes the design of an integrated electrical stimulator system capable of generating a trapezoidal, charge-balanced, biphasic stimulus output with a near-zero DC level. By addressing the limitations of existing Bio DAQ systems, this research aims to provide a practical, user-friendly, and cost effective solution that significantly improves the quality of life for patients who require long term data acquisition and stimulation. The specific thesis objectives are listed below:

- Objective 1: To Develop a Reliable Circuit for the Biopotential Data Acquisition System (Bio DAQ): The first objective is to design a compact, low-cost, wireless, 16 - channel Biopotential Data Acquisition (Bio DAQ) System that reliably acquire physiological data and send it wirelessly at a high transfer rate in real-time with a low energy consumption. The system will have several novel and flexible design approaches like; (1) It has user selectable digital filter in each channel based on the signal frequencies like EMG, EEG, ECG, EOG. The same system will be used to acquire different signals simultaneously. (2) It has variable gain and configurable analog bandpass filter. (3) It can acquire signals from 4 patients simultaneously. (4) The system can able to acquire signal from both two-electrode as well as three-electrode configurations. This involves designing analog front end (AFE), wireless unit, microcontroller unit (MCU), user interface and power supply unit. The development process includes schematic design, component selection, PCB layout, and rigorous testing. The goal is to overcome limitations of existing devices by enhancing user comfort, mobility, and flexibility.

- Objective 2: To Develop an Integrated Electrical Stimulator: The second objective is to design an innovative integrated stimulator which produce microcontroller-based charge-balanced waveform of trapezoidal shape which are particularly effective in providing comfortable and strong muscle stimulation while avoiding sudden, uncomfortable responses. Additionally, the stimulator features an adjustable frequency and pulse width, which can be modified using a controllable knob, allowing users to set the parameters to their preferred settings. The development process includes schematic design, component selection, PCB layout, and testing. The goal is to overcome limitations of existing devices by reducing adverse effects of stimulation and maintain patient safety over extended use.
- Objective 3: To Test and Evaluate the Developed Bio DAQ System: The third objective is to test and evaluate the effectiveness and safety of the developed Bio DAQ system as per various international standards. The developed system will achieve wireless signal transmission range of at least 30m without any signal distortion comparable to commercial-grade systems. The system will maintain reliable operation across different biopotential signal types (ECG, EMG, EEG, EOG) under real-world conditions. This involves validation of our design through conducting various tests as per international standards like – (1) Electrical safety test as per IEC 60601-1 standard, (2) Electromagnetic Interference (EMI) test as per CISPR 11 standard, (3) Functional test using simulators as well as real life signals. This assesses the system's ability to acquire normal signals as well as various critical signals/arrhythmias like atrial flutter, atrial fibrillation, second degree heart block, first degree heart block etc through simulator. The goal is to confirm the device's viability as a practical data acquisition device, and ensure it is safe for long-term use.

1.9 Thesis Outline

This thesis is structured into five chapters, each addressing a critical aspect of the development and evaluation of the wireless Bio DAQ system.

Chapter 1 establishes the foundation for the thesis by presenting an extensive description of origin of biopotential, different types of biopotential signals like EEG, EOG, EMG, ECG etc with their characteristics and significance. This chapter illustrates the biopotential data acquisition (Bio DAQ) system and limitations of the current Bio DAQ systems like most of the systems are wired systems which restrict mobility and patient comfort; designed for specific signals like EMG, EOG, EEG; not suitable for animal studies and non-availability of integrated stimulator. The chapter outlines the specific objectives of the research, which include development of wireless Bio DAQ system with user-selectable digital filters, configurable analog bandpass filters, and the ability to acquire different signals from multiple patients while ensuring low power consumption and real-time data transmission. It will also have an integrated innovative stimulator that enhances patient comfort, and ensuring safe electrical stimulation. It also describes the organization of the thesis and the rationale behind the chosen research approach.

In **Chapter 2,** we present an extensive literature review on wireless Bio DAQ system. This chapter provides a comprehensive review of the latest wireless Bio DAQ systems, covering their applications, signal acquisition methods, design methodologies, and wireless technologies. It highlights key aspects such as signal processing, noise reduction techniques, and the benefits of wireless systems over traditional wired setups. This review serves as a valuable resource to emphasize the potential of wireless Bio DAQ systems for continuous and remote physiological monitoring. The findings underscore the need for future research to improve signal processing, enhance accuracy, develop non-signal-specific Bio DAQ systems, and integrate electrical stimulators that minimize adverse effects while ensuring patient safety during prolonged use.

In **Chapter 3,** we describe the development of the circuit and subsystem for the wireless Bio DAQ system. The chapter starts with the general challenge and targeted objective of the design. This is followed by methods of development of several subsystems like Analog Front End (AFE), Microcontroller Unit (MCU), wireless system, power supply, user interface, integrated stimulator, and firmware development. It will describe the different stages of development like from initial schematic design to the final PCB layout and breadboard implementation of the circuit. We explored various circuit designs to finalize a configuration that meets our objectives.

Chapter 4 details the development of a fully functional prototype by integrating key subsystems, including the Analog Front End (AFE), Wireless Module, Microcontroller Unit (MCU), Stimulator Module, Power Supply, and Display Unit. The process begins with circuit implementation on a breadboard, followed by iterative testing, and culminates in a compact, single PCB module. The chapter covers: (1) Breadboard Testing: Ensuring individual subsystems function correctly before integration, resolving early-stage challenges. (2) PCB Integration: Optimizing layout for signal integrity, noise reduction, and reliable communication between modules. (3) Testing & Validation: Conducting electrical safety (IEC 60601-1) and electromagnetic interference (CISPR 11) tests as per international standards, along with real-life biopotential signal acquisition to confirm system reliability. The results validate the prototype's effectiveness, demonstrating its capability to acquire high-quality biopotential signals and meet its intended objectives.

Chapter 5 summarizes the key findings of the research and discusses their implications. It highlights the contributions of the thesis to the field of wireless Bio DAQ technology, including advancements in flexibility approach and reconfigurability in circuit design, development of new integrated stimulators, enhancing safety and user comfort. The chapter also outlines potential directions for future research, suggesting areas for further development to enhance the system's capabilities and broaden its applicability. This concluding chapter emphasizes the significant progress made and sets the stage for continued innovation in wireless Bio DAQ technology.

CHAPTER – 2

Literature Review

Chapter 2
Literature Review

2.1 Introduction

Biopotential data acquisition systems are advanced tools designed for medical and research applications to capture and amplify the electrical signals produced by the body. These devices play a critical role in obtaining precise and high-quality data from various physiological sources. Over the years, numerous devices have been developed for biosignal acquisition, catering to signals like ECG, EOG, EEG, and EMG. Most of these devices are specifically engineered with hardware optimized for the amplitude and frequency ranges of the targeted signals. However, a large proportion of these systems remain wired, leading to limitations such as inconvenience during animal studies and discomfort for patients during extended signal monitoring sessions [2]. The emergence of wireless biopotential amplifier data acquisition devices has addressed these challenges, offering enhanced flexibility and improved comfort for users and patients alike [17].

Various methodologies have been utilized in the development of wireless Bio DAQ devices, spanning from fully analog systems that integrate transmitters, amplifiers, and receivers to more sophisticated microprocessor-based and system-on-chip (SoC) solutions. Additionally, hybrid systems that combine SoC-based analog front ends (AFE) with transmitter and receiver modules have also emerged. Each of these approaches offers distinct advantages and limitations, emphasizing the need for a comprehensive evaluation. However, despite the diversity in design, there remains a lack of a systematic review that consolidates and critically assesses these technologies.

In this chapter, we provides a systematic review of various wireless Bio DAQ devices and their diverse applications. It explores the signal acquisition and wireless transmission techniques used to extract meaningful insights from biosignals, emphasizing methods for signal processing and noise reduction. The study also addresses the developmental challenges encountered by manufacturers and researchers, while highlighting the advantages these devices offer over traditional wired systems. This review helps in understanding the advancements in wireless Bio DAQ devices, research gap in current systems and the transformative potential for wireless Bio DAQ systems for healthcare, particularly in continuous and remote physiological monitoring [17].

2.2 Literature Survey

Starting December 1, 2023, an extensive literature search was conducted using platforms such as Google Scholar, ResearchGate, IEEE Xplore, and SCOPUS. The search utilized key terms like "biopotential," "amplifier," "data acquisition," "stimulator," "wireless," "ECG," "EOG," and

"EMG." To enhance the research depth, references within the collected articles were also thoroughly reviewed. To uphold academic rigor and prioritize peer-reviewed content, non-English articles and conference abstracts were excluded. Duplicate studies were identified and removed by meticulously comparing author names, journal titles, and publication dates. We have screened around 1296 papers and a comprehensive study was made on 40 papers based on their relevance and depth of information. The flowchart of the literature search is shown in Figure 2.1 [17].

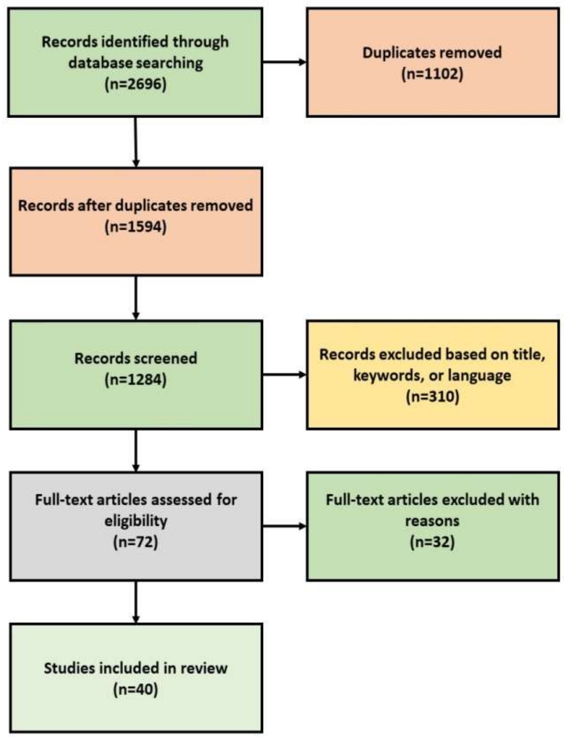


Figure 2.1 Literature Survey

A comprehensive study was undertaken, incorporating a selection of 40 papers chosen for their relevance and depth of information. A thorough analysis of these papers revealed several key insights, offering valuable contributions to the understanding and advancement of the subject matter.

After thoroughly reviewing the selected papers, we compiled a comprehensive table (Table 2.1) that presents key details, including the author's name, device/developer, category parameters, power supply, number of channels, transmission method/standard, availability of an integrated stimulator, wireless transmission range, power consumption, and insightful remarks. This table serves as a valuable reference, offering a structured comparison of various systems and their specifications

Table 2.1 Comparison Table

Sl No	Paper Ref.	Author	Name of the device/ Developed by	Category	Parameters	No of Channels	Transmission Method / standard	Integrated Stimulator	Power Consumption	Power Supply	Wireless Transmission Range	Remarks
1	[18]	I. Obeid, M. Nicolelis, and P.Wolf	Duke University	Microprocessor based	EEG	12	802.11b	No	4.0W	3.3V & 5V	9m	The system is tested in animals only
2	[19]	S. Farshchi, A. Pesterev, P. H. Nuyujukian, I. Mody and J. W. Judy	Bi-Fi/University of California	Microprocessor based	EEG, ECG, SpO2 and Heart rate	8	Bluetooth	No	97mW	3V	9m	
3	[20]	P. Mohseni, S. Eliades and K. Najafi,	Michigan University	Analog system	EEG	4	TDMA/ Analog FM	No	2.05mW	± 1.5V	a few meters	
4	[21]	A. Nieder	Massachusetts Institute of Technology	Analog system	EEG	2	Analog FM	No	--	± 1.40 V	a few meters	It is tested on Barn Owl
5	[22]	S. Takeuchi and I. Shimoyama	Tokyo University	Analog system	EEG	1	Analog FM	No	10mW	3V	16m	This is an implantable microelectrode specifically designed for recording of neural activity of insects.
6	[23]	M. Modarreszadeh and R. Schmidt	Cleveland Medical Devices	Analog system	EEG	32	FSK	No	--	9V	<46 m	It is tested on Hum

			Inc									ans
7	[24]	C. Mundt, K. Montgomery, U. Udoh, V. Barker, G. Thonier, A. Tellier,R. Ricks, R. Darling, Y. Cagle, N. Cabrol	NASA	Microprocessor based	ECG, Respiration rate, Temperature, SpO2, Heart rate, three axes acceleration	10	Bluetooth	No	360mW	3V	10m	It is tested on Humans
8	[25]	M. Rasid and B. Woodward	Loughborough University	Microprocessor based	ECG, Temperature, SpO2, Heart rate, Blood pressure	4	Bluetooth	No	4.5W	9V	--	
9	[26]	J. Yao, R. Schmitz, and S. Warren	Kansas State University	Microprocessor based	ECG, SpO2	5	Bluetooth	No	3.44W	6V	--	
10	[27]	T. Fulford Jones, G. Wei, and M. Welsh	Harvard University	Microprocessor based	ECG, SpO2	2	Zigbee	No	100mW	3V	9m	
11	[28]	P. Irazoqui-Pastor, I. Mody, and J. W. Judy	University of California	Analog System on Chip (SoC)	EEG	1	Analog FM	No	5-8mW	2-3.2V	0.5m	Single implantable Chip. It is tested on rodent
12	[29]	E. A. Johannessen et al	University of Glasgow	Microprocessor based	Temperature, pH, conductivity, and dissolved oxygen	4	TDMA/FSK	No	12.1mW	3.1V	1m	Hybrid system
13	[30]	Farshchi, Shahin &Nuyujukian, Paul &Pesterev, Aleksey & Mody, Istvan & Judy, Jack	University of California	Microprocessor based	EEG	6	MCFSK	No	66mW	3V	9m	
14	[31]	Liu, Xilin & Zhang, Milin & Xiong, Tao & Richardson, Andrew & Lucas, Timothy & Chin, Sang & Etienne-Cummings, Ralph & Tran, Trac & Van der Spiegel	University of Pennsylvaniaa	Microprocessor based	EEG	16	Bluetooth	No	254µW (For implantable chip only)	--	5m	Hybrid Implantable System on Chip with exter

												nal wireless relay
15	[32]	Fall, C. L. & Gagnon-Turcotte, Gabriel & Dube, Jean-Francois & Gagne, Jean & Delisle, Yanick & Campeau-Lecours, Alexandre & Gosselin, Clement & Gosselin, Benoit	Laval University	Microprocessor based	EMG	3	FSK	No	--	--	--	
16	[33]	Borromeo, S. & Rodriguez-Sanchez, M.C. & Machado, Felipe & Hernandez Tamames, Juan Antonio & Prieta, R.	Rey Juan Carlos University	Microprocessor based	ECG	1	Bluetooth	No	--	--	--	
17	[34]	Klum, Michael & Leib, Fabian & Oberschelp, Casper & Martens, David & Pielmus, Alexandru Gabriel & Tigges, Timo & Penzel, Thomas & Orglmeister, Reinhold.	Technische University	Microprocessor based	stethoscope, ambient noise sensing, ECG, impedance pneumography (IP) and 9-axial actigraphy.	5	Bluetooth	No	--	--	--	
18	[35]	Cerone GL, Giangrande A, Ghislieri M, Gazzoni M, Piitulainen H, Botter	SynU/Politecnico di Torino	Microprocessor based	EEG, sEMG	33	Wi-Fi	Not integrated, but provision is there	32.5mW	3.3V, 5V	--	
19	[36]	Paul A, Lee MS, Xu Y, Deiss SR, Cauwenberghs G	weDAQ/University of California	Microprocessor based	EOG, EMG, EEG, ECG	16	Wi-Fi	No	228.1 mW	3.7V	10feet	This device is dedicated for in ear applications
20	[37]	Frerichs I, Vogt B, Wacker J, Paradiso R, Braun F, Rapin M, Caldani L, Chetelat O,	University Medical Center Schleswig-	Microprocessor based	ECG, SpO2, Electrical impedance, Respirati	--	Bluetooth	No	--	--	--	

		Weiler N	Holstein		on rate, heart rate, activity/posture						
21	[38]	K. Petkos et al	Imperial College London	Analog system	EEG, EMG, ECG, ECoG, Accelerometer	8	Zigbee	No	--	3.7V	5m	
22	[39]	Siddharth, A. N. Patel, T. P. Jung, and T. J. Sejnowski	University of California	Microprocessor based	PPG, EEG, eye-gaze, body motion capture, GSR	16	Wi-Fi	No	--	3.7-5V	--	
23	[40]	R. Kaveh et al	University of California	Microprocessor based	EEG, EOG	64	Bluetooth	No	46mW	3.5-6V	--	This device is dedicated for in ear applications
24	[41]	V. K. Sarker, M. Jiang, T. N. Gia, A. Anzanpour, A. M. Rahmani and P. Liljeberg	University of Turku	Microprocessor based	ECG, EMG	8	Bluetooth	No	--	3.7V	--	
25	[42]	Wang LH, Chen TY, Lin KH, Fang Q, Lee SY	National Cheng Kung University	System on Chip (SoC)	ECG	1	Zigbee	No	25.32 mW	1.2V	--	
26	[43]	Morrison T, Nagaraju M, Winslow B, Bernard A, Otis BP	University of Washington	System on Chip (SoC)	ECG	4	Digital FSK	No	1.07-1.73mW	1.2-1.45V	20m	
27	[44]	da Silva HP, Lourenço A, Fred A, Martins R	BIT/Instituto Superior Técnico	Microprocessor based	EMG, ECG, Electrodermal Activity (EDA) and Accelerometry (ACC)	6	Bluetooth	No	--	3.7V	10m	Separate front end hardware for ECG, EMG, EDA etc
28	[45]	D. Fan, D. Rich, T. Holtzman, P. Ruther, J. W. Dalley, A. Lopez, M. A. Rossi, J. W. Barter, D.	Duke University	Analog system	EEG	15	FM	No	--	3V	4m	It is tested on mouse

		Salas Meza, S. Herwik, T. Holzhammer, J. Morizio, and H. H. Yin									
29	[46]	R. R. Harrison, H. Fotowat, R. Chan, R. J. Kier, R. Olberg, A. Leoardo, and F. Gabbiani	University of Utah	Analog system	EEG, EMG	4	Digital FSK	No	1mW	1.5V	2m	It is tested on insect and small animals
30	[57]	S. Debbarma, S. Nabavi and S. Bhadra	McGill University	Microprocessor based	EOG	1	Bluetooth	No	52.8mW	3.3V	--	
31	[47]	Zhou A, Santacruz SR, Johnson BC, Alexandrov G, Moin A, Burghardt FL, Rabaey JM, Carmena JM, Muller R	University of California	Microprocessor based	EEG	128	Bluetooth	Yes	172mW	4.1V		
32	[48]	Song MS, Kang SG, Lee KT, Kim J	Kwangwoon University	Microprocessor based	EMG	1	Bluetooth	No	--	5V	--	
33	[49]	Von Luhmann A, Wabnitz H, Sander T, Muller KR	Berlin Institute of Technology	Microprocessor based	EEG, fNIRS, Accelerometer	4+2 Bioelectrical channel 4+2 fNIRS channel	Bluetooth	No	360mW	3.7V	5m	
34	[50]	Gagnon Turcotte G, Cote Allard U, Mascret Q, Torresen J, Gosselin B	Universite Laval	Microprocessor based	ECG, EMG, EDA, photoplethysmography, skin temperature, actigraphy	--	Bluetooth	No	--	--	--	
35	[51]	Perez Vidal C, Gracia L, Carmona C, Alorda B, Salinas A.	Miguel Hernandez University	Microprocessor based	ECG	4	Zigbee	No	--	3.3-6V	--	
36	[52]	Srivastava A, Sankar K N, Chatterjee B, Das D, Ahmad M, Kukkundoor RK, Saraf V,	Bio-WiTel/Indian Institute of Technolo	System on Chip (SoC)	ECG, photoplethysmography	--	FSK	No	250µW+990µW	1-1.8V	3m	

		Ananthapadmanabhan J, Sharma DK, Baghini MS	gy, Bombay									
37	[53]	Lee SY, Hong JH, Hsieh CH, Liang MC, Chang Chien SY, Lin KH	National Cheng Kung University	System on Chip (SoC)	ECG	1	OOK Modulation (ASK)	No	1.5mW	1.2V	--	
38	[54]	Gomez Correa M, Cruz Ortiz D	Universidad de Antioquia	Microprocessor based	EMG	4	Wi-Fi	No	--	3.7V	--	It is tested on human and algorithm is also made to analyze EMG signals.
39	[55]	Wei Y, Cao Q, Hargrove L, Gu J	Northwestern University	System on Chip (SoC)	ECG, EMG	6	Bluetooth	No	30+280μW	0.6-1.2V	--	
40	[56]	Kneisz L, Unger E, Lanmuller H, Mayr W	Medical University of Vienna	Microprocessor based	EMG	2	Bluetooth	Yes	73mW	3.6V	10m	This system is implantable with FES for large animals

2.3 Literature Analysis

Song [61] made a groundbreaking contribution by developing a fully integrated single-chip system for biopotential signal acquisition, digitization, and telemetry. This innovation marked a significant advancement in the field. The system features a custom-designed preamplifier and a sigma-delta ADC converter, which connects to one of two ring oscillators—spaced 400 kHz apart—via a multiplexer circuit to generate an FSK signal. Remarkably compact, the system measures just 2.5 x 2.5 mm and operates without requiring off-chip components, except for a 2 cm antenna and a battery. It achieves efficient power consumption, drawing only 10 mW from an external 2.5V supply [30]. Likewise, Irazoqui Pastor [28] at the University of California developed an inductively powered single-channel wireless neural recording system, closely resembling the design pioneered by P. Mohseni et al. [20].

In a different approach, I. Obeid et al. [18] created a wireless neural recording system initially targeting owl monkeys instead of rodents, which allowed for less restrictive constraints on weight and power consumption. This led to the use of commercially available off-the-shelf (COTS) PC components, enabling advanced signal processing and communication capabilities. A. Neider et al. at Aachen University also adopted a COTS-based strategy, linking two neural preamplifier circuits to the inputs of a commercially available FM stereo transmitter. This configuration facilitated the simultaneous transmission of two channels of single-unit activity, which were subsequently demodulated by a commercial FM stereo receiver for further analysis [21].

Cleveland Medical Devices has introduced a product [23] to the market in this domain, although detailed design specifics remain unavailable due to proprietary constraints. Operating within the 902 MHz to 928 MHz frequency band and employing frequency shift keying (FSK) for data transmission, the device demonstrates notable functionality. However, its dependence on a bulky 9V battery, combined with relatively large dimensions (6.4 x 5.1 x 1 cm) and a weight of 68 g, indicates significant reliance on commercial off-the-shelf (COTS) components.

Over time, research has increasingly focused on systems capable of acquiring multiple signals simultaneously, such as ECG, EMG, EEG, EOG, temperature, and SpO2, often featuring higher channel counts, as demonstrated in [2,19,24,25,29,34,36,38-41,44,49,50].

In Table 2.1, we primarily compare three system architectures: 1) Fully analog systems, 2) Microprocessor-based systems, and 3) System-on-Chip (SoC) systems. Fully analog systems, characterized as analog telemetry systems, lack onboard digital signal processing or data compression capabilities. Despite their simplicity, they are significantly smaller and have lower power consumption compared to microprocessor-based systems. However, they have limitations, including the need for custom receivers and an inability to communicate using standard protocols like Health Level 7 (HL7) or IEEE.

Microprocessor-based systems, on the other hand, offer extensive signal processing and robust communication capabilities. However, they are power-intensive and often larger in size. SoC solutions provide a compact, power-efficient alternative by integrating specialized components onto a single chip. While they address many challenges, the development of custom Integrated Circuits (ICs) for specific applications such as biosignal acquisition and processing—especially in non-standardized fields like biological signal recording—can be economically prohibitive. This contrasts with applications like cellular phones, which adhere to established international standards such as GSM (Global System for Mobile Communications) or Bluetooth [19]. The features, benefits, and drawbacks of these systems are further detailed in Table 2.3.

From Table 2.1, it is evident that, in addition to the design approaches, several key parameters have significantly influenced the development of wireless biosignal acquisition devices. These parameters include the number of channels, transmission methods, integrated stimulators, power consumption, and the choice of wireless technology. Each of these factors has played a critical role in shaping the functionality, efficiency, and usability of these systems. The details and implications of these parameters are discussed below.

2.3.1 Number of Channels

The number of channels in a biopotential data acquisition system signifies its ability to record or monitor multiple biosignals simultaneously. This capacity is vital for capturing a comprehensive range of physiological data, which is essential in advanced biomedical research and clinical applications. Multi-channel systems enable researchers and clinicians to simultaneously monitor several biological signals, allowing a holistic view of a subject's physiological state. This expanded monitoring capability supports the analysis of intricate body functions and interactions, which would otherwise be challenging with single-channel systems.

A higher channel count greatly benefits specific applications in biomedical research and healthcare. For instance, in neurophysiology, multi-channel systems facilitate the observation of motor units, providing critical insights into muscle function and coordination. Similarly, multi-channel acquisition is instrumental in emotional analysis, as it allows the tracking of subtle facial muscle activities that correlate with emotional states. In the field of physical rehabilitation and human-machine interface research, multi-channel electromyography systems are used to recognize hand gestures by measuring electrical signals from multiple muscle groups in the arm. These applications underscore the importance of multi-channel devices in capturing nuanced and detailed physiological information.

Moreover, in sleep studies and other long-term monitoring scenarios, the ability to record multiple signals, such as brain activity through electroencephalography (EEG), heart rate via electrocardiography (ECG), and eye movement using electrooculography (EOG), is invaluable. These multi-modal approaches enable a comprehensive understanding of complex physiological processes like sleep patterns and disorders. By leveraging multi-channel biopotential systems, researchers and clinicians can achieve more accurate diagnoses, tailor treatment plans, and further explore the intricate relationships between various physiological signals [41, 62-65].

2.3.2 Transmission Method

The transmission method or standard employed in Bio DAQ systems plays a pivotal role in determining how data is relayed from the device to a display unit or processing system. These methods can be broadly categorized into wired and wireless connections. Wired options, such as USB and Ethernet, are known for their reliability and high data transfer rates, making them suitable for stationary setups and applications requiring continuous, high-bandwidth data flow. However, they limit patient mobility and are less ideal for wearable or portable applications, particularly in scenarios requiring freedom of movement or flexibility.

Wireless technologies, on the other hand, have revolutionized biosignal transmission by enabling mobility and convenience. Among these, Bluetooth is widely used for its low power consumption and minimal latency, making it particularly advantageous for real-time applications, such as monitoring heart rate or muscle activity during physical therapy. Its typical range of up to 10 meters suits personal and close-proximity monitoring scenarios. However, its lower data transfer rate may pose challenges in applications requiring the simultaneous acquisition and transmission of large datasets.

Wi-Fi, by contrast, offers significantly higher data transfer rates and an extended range, often reaching several hundred meters. This makes it ideal for use in larger spaces, such as hospitals or residential settings, where multiple devices can connect to a single network. However, Wi-Fi's higher power consumption and potential for network interference require careful consideration, especially for battery-operated or wearable devices. Ultimately, the choice of transmission method is guided by various factors, including the application’s range requirements, data rate demands, power constraints, latency tolerance, and compatibility with existing systems, ensuring optimal performance for diverse biosignal acquisition needs.. [17].

2.3.3 Integrated Stimulator

An integrated stimulator in a Bio DAQ system denotes its ability to deliver controlled stimuli, such as electrical pulses, alongside acquiring signals. This functionality is especially valuable in experimental or therapeutic settings requiring simultaneous stimulation and data collection. Only a limited number of devices [35,47,56] combine stimulation with biosignal acquisition. One significant application of this integration is in the development of devices like Functional Electrical Stimulators (FES), where the stimulus parameters—such as frequency and pulse width —can be customized based on patient data obtained before and after stimulation [2, 14, 56]. Additionally, integrated stimulators are instrumental in evaluating the effectiveness of various muscle stimulation techniques.

2.3.4 Power Consumption

Power consumption is a critical consideration in the design and operation of Bio DAQ systems. It dictates the amount of electrical energy required during the device's operation, directly impacting its efficiency, portability, and practicality. Devices with lower power consumption are particularly advantageous for portable or wearable applications, as they extend operational times between recharges or battery replacements, enhancing convenience and usability for both patients and healthcare providers. This feature becomes especially important in scenarios such as long-term monitoring or in environments where frequent access to power sources is limited. Efficient power consumption also contributes to reducing heat generation, ensuring user comfort and device reliability over extended use.

The power supply specification of a Bio DAQ system further influences its deployment and compatibility with available power sources. Devices may rely on batteries, external power sources, or a combination of both, with the choice affecting their flexibility and usability in various contexts. Battery-powered systems offer mobility and ease of use but require careful management to balance power consumption and battery life. On the other hand, systems that integrate external power sources may be better suited for stationary applications but lack the portability needed for mobile monitoring. The compatibility of these power systems with existing infrastructure is also a key factor in determining their adoption in clinical or research settings.

Among the different technological approaches, fully analog devices and System-on-Chip (SoC)-based systems have demonstrated significantly lower power consumption compared to microprocessor-based systems. References [20-22, 28, 42, 43] highlight the impressive energy efficiency of analog and SoC-based devices, with power requirements typically ranging from 1 to 14 mWs. These characteristics make them particularly well-suited for energy-sensitive applications, such as implantable devices or long-term physiological monitoring. In contrast, microprocessor-based systems, as noted in [18-19, 24-27, 29-37, 39-41, 44, 47-51, 54-56], tend to consume more power due to their advanced processing and communication capabilities. While these systems offer enhanced functionality, their higher power requirements may limit their use in portable or battery-reliant applications, underscoring the importance of balancing power efficiency with technological capabilities.

2.3.5 Wireless Transmission Range

Wireless transmission range is a key factor in the design and functionality of Bio DAQ systems, especially for applications where mobility is essential. A longer transmission range provides significant flexibility, allowing the placement of the acquisition system and its receiving unit in various positions without compromising performance. This adaptability is particularly advantageous in dynamic or large-scale environments, such as hospitals, laboratories, or home healthcare setups, where users may need to move freely or accommodate multiple patients. Additionally, a system with an extended range can support remote monitoring in cases where the acquisition device is placed far from the healthcare provider or monitoring station.

The flexibility offered by a robust wireless range enhances both comfort and convenience for users. For instance, patients can move around freely within the monitored area without being tethered to a specific location. This is especially beneficial for long-term monitoring applications, such as sleep studies or wearable devices, where patient mobility and comfort are priorities. Furthermore, reliable transmission reduces the risk of signal loss or interruptions caused by interference or physical obstructions. This ensures the continuous flow of accurate and high-fidelity biosignal data, a critical factor in effective diagnostics and therapeutic interventions.

Different wireless technologies offer varying ranges and capabilities, catering to diverse application requirements. Bluetooth, as noted in devices referenced in [19, 24, 31, 44, 49, 56], is often limited to a range of approximately 10 meters. While this shorter range suffices for close-proximity monitoring and offers advantages like low power consumption and minimal latency, it may not be suitable for larger environments. On the other hand, Wi-Fi and digital modulation-based systems, such as the one detailed in [23], can extend up to 46 meters. These technologies support broader operating distances and higher data transfer rates, making them ideal for applications requiring extensive coverage or high-volume data transmission, such as hospital-wide patient monitoring systems.

2.4 Evolution of Wireless Bio DAQ Systems

The evolution of wireless Bio DAQ systems has been a remarkable journey that has significantly impacted healthcare, research, and personal well-being. Bio DAQ systems are designed to stand apart from conventional medical devices, offering enhanced portability, user-friendly operation, and adaptability to various environmental conditions [58]. Initial Bio DAQ systems were wired and bulky. Early electroencephalogram (EEG) and electrocardiogram (ECG) machines were used primarily in clinical settings, requiring extensive wiring and limiting mobility. In the 1960s-1970s, telemetry was introduced in Bio DAQ systems. Telemetry technology allowed for the wireless transmission of biosignals from the patient to monitoring equipment. This reduced the constraints posed by wires, enabling more freedom of movement for patients. However, these systems were still relatively large and often limited to hospital use. In 1980s-1990s, miniaturizations and ambulatory monitoring concepts were developed. Advances in microelectronics and battery technology led to the miniaturization of Bio DAQ systems. This allowed for the development of portable and ambulatory monitoring systems, enhancing patient comfort and expanding applications beyond hospitals.

After the development of wireless communication standard in 2000s, the development of wireless biosignal acquisition devices started. The adoption of standardized wireless communication protocols, such as Bluetooth and Wi-Fi, further improved the versatility and interoperability of Bio DAQ systems. This facilitated seamless integration with other devices and systems, making data collection and analysis more efficient. The emergence of wearable technology in the 2010s marked a significant shift. Biosensors embedded in devices like smartwatches and fitness trackers enable continuous monitoring of biosignals in daily life. This consumer-driven approach promoted preventive healthcare and wellness.

MEMS technology is employed in the development of implantable devices, as highlighted by Kiourti et al [59]. These devices were introduced into the body through surgeries or medical procedures, either fully or partially. Consequently, the design of implantable devices is crucial to ensure they do not adversely impact health. Notable examples of such devices in the biomedical research domain include tattoo-based glucose detection devices, cardiac pacemakers, electronic tattoos (e-tattoos), ‘Abbot Confirm RX’ implantable devices, and bio-sensitive inks (bioinks).

In the realm of non-invasive methods for obtaining fluid information from the human body, ingestible sensors play a significant role [60]. These sensors are capable of monitoring various hormones and enzymes around the abdomen, as well as providing biometric information. A particular category of ingestible sensors includes pills designed for monitoring fluid levels in the human body. Upon ingestion, these pills are activated by stomach acid through chemical reactions, sending signals to a body patch. This patch enables the monitoring of various physiological parameters, including heart rate (HR), pH, blood pressure (BP), and body temperature, while also facilitating external communication. The incorporation of wireless technology in both implantable and ingestible devices allows for the smooth transmission of collected information without the risk of data loss. Furthermore, this integration ensures the uninterrupted functionality of the device and enables continuous monitoring of the battery status.

The integration of Bio DAQ systems into the Internet of Things (IoT) ecosystem allowed for real-time data transmission and remote monitoring. This connectivity enabled healthcare professionals to monitor patients remotely and facilitated data-driven healthcare management. In the 2020s, the integration of artificial intelligence (AI) and machine learning (ML) has further revolutionized biosignal devices. These technologies enable real time analysis of biosignals, providing insights into health conditions, predicting anomalies, and personalizing healthcare interventions. The rollout of 5G technology has further improved data transfer speeds and reduced latency, enabling faster and more reliable communication between biosignal devices and data processing systems. This has implications for real-time monitoring and telemedicine applications. Block chain technology has been explored further to enhance the security and privacy of biosignal data. Decentralized approaches may empower individuals to have more control over their health data, fostering a new era of personalized and patient-centric healthcare. Modern wearable devices are designed with diverse functionalities, functioning akin to microcomputers. They facilitate the integration of the entire system, encompassing data collection, processing, and external communication authorization. The different stages of the evolution of wireless Bio DAQ systems with their characteristics are shown in Table 2.2.

Table 2.2 Evolution of Wireless Bio DAQ Systems

Stage	**Characteristics**
Early Stage	• Introduction of basic biosignal monitoring devices. • Wired connections and bulky equipment. • Limited mobility and inconvenience for users.
Transition Phase	• Emergence of wireless technologies.

	• Introduction of bluetooth and other short-range wireless protocols. • Reduction in device size and increased portability.
Intermediate Stage	• Advancements in MEMS technology. • Integration of wireless communication in implantable devices. • Improved data transmission and connectivity.
Current Stage	• Proliferation of wireless biosignal devices in healthcare. • Use of advanced wireless protocols {e.g.Wi-Fi, NFC(Near Field Communication)}. • Enhanced accuracy, real-time monitoring, and extended battery life.
Recent Innovations	• Incorporation of IoT (Internet of Things) in biosignal devices. • Integration with smartphones and other smart devices. • Cloud connectivity for remote monitoring and data storage.
Future Trends (Projected)	• Continued miniaturization of devices. • Integration of AI for real-time data analysis. • Enhanced biocompatibility for implantable devices. • Development of more sophisticated biosensors.

2.5 Different Design Approaches

A variety of Bio DAQ systems are available in the market, with most tailored to specific signals such as EMG, ECG, and EEG. However, the majority of these systems rely on wired configurations, which present challenges like incompatibility with animal studies and discomfort for patients during prolonged signal acquisition [2]. To mitigate these issues, wireless biosignal acquisition systems have been developed, offering improved flexibility and user comfort [17].

A key challenge in designing remote Bio DAQ systems lies in developing compact wireless biological sensors that serve as a bridge between patients and network infrastructure. These sensors must be capable of detecting, amplifying, and transmitting biological signals ranging from microvolts to millivolts. To ensure practicality, the sensors should be discreet, compact, and energy-efficient to maintain sufficient battery life [19].

The radio transmitter, which handles signal transmission, is the primary consumer of power in these devices. Integrating local data-processing capabilities can significantly enhance battery life by reducing the need for continuous high-bandwidth data transmission. Additionally, incorporating onboard signal processing with a receiver enables user-defined multimode functionality. This feature allows the system to toggle between low-power event detection and adaptive real-time signal transmission. Thus, a system combining bidirectional communication with onboard computational abilities offers a substantial advantage over basic transmitter/receiver setups [17]. Various approaches to developing such advanced wireless systems are explored in the following sections.

2.5.1 Fully Analog Systems

A fully analog wireless Bio DAQ system consists of several key components working in unison to capture, process, and transmit biological signals while avoiding digital conversion. These systems are constructed using either fully integrated amplifiers and transceivers or multichip module assemblies. The primary components include biosignal sensors, an Analog Front End (AFE), wireless transmitters, an antenna, a wireless receiver, an analog back end, output or display devices, and a power management unit [17].

A general architecture of such a system is depicted in Figure 2.2 [17]. This design emphasizes maintaining the signal in its analog form throughout the acquisition and transmission phases, postponing digital conversion until later stages of signal processing. By doing so, it aims to minimize power consumption and preserve signal fidelity. Several analog systems have been developed to date [20-23, 28, 38, 45-46] and described in Table 2.1.

While the fully analog devices discussed in citations [20-21, 28] offer compact sizes (ranging from 5–100 mm) and low power consumption (approximately 2–14 mWs), they lack advanced features such as digital signal filtering and bidirectional communication. An exception is the system described in [21], which incorporates an inductive power link for communication between the base station and the sensor. However, even minor upgrades or modifications—such as increasing channel count or signal bandwidth—may require extensive reintegration efforts [17].

Assembled multichip modules that utilize Commercial Off-The-Shelf (COTS) components for amplifiers and transmitters (as exemplified in [21-23]) deliver similar performance to those employing custom ICs. Nevertheless, these systems often come with trade-offs, including longer physical dimensions, increased weight, higher power consumption, and shorter development times [19].

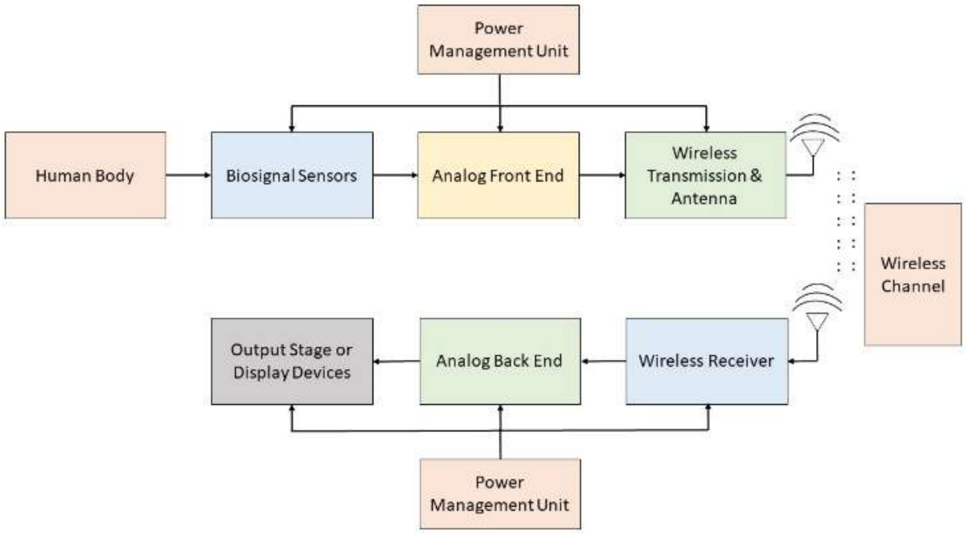


Figure 2.2 General architecture of a Fully Analog System

2.5.2 Microprocessor Based Systems

A microprocessor-based wireless Bio DAQ system integrates digital processing capabilities with wireless communication functions. This integration enhances the system's flexibility, allows for advanced signal processing techniques, and ensures seamless wireless data transmission, making it well-suited for diverse biomedical monitoring applications. Such a system typically comprises biosignal sensors, an Analog Front End (AFE), a microprocessor or microcontroller, a Digital Signal Processing (DSP) unit, memory, a wireless transceiver, a user interface and display, a software stack, and a power management unit. The general architecture of this system, showcasing its components and workflow, is illustrated in Figure 2.3 [17].

Microprocessor-based wireless Bio DAQ systems provide significant advantages in signal processing capabilities and remote monitoring. However, they also face challenges such as higher power consumption, increased complexity, and potential interference. Despite demonstrating commendable signal processing and bidirectional communication capabilities [2, 18-19, 24-27, 29-37, 39-41, 44, 47-51, 54-56], these systems are typically larger, heavier, and consume more power compared to the fully analog integrated systems discussed earlier. Additionally, the data throughput and processing performance of these systems often fail to fully exploit the potential of their hardware. This is primarily due to the lack of digital signal filtering in many instances, resulting in inefficient use of hardware and elevated power consumption [17].

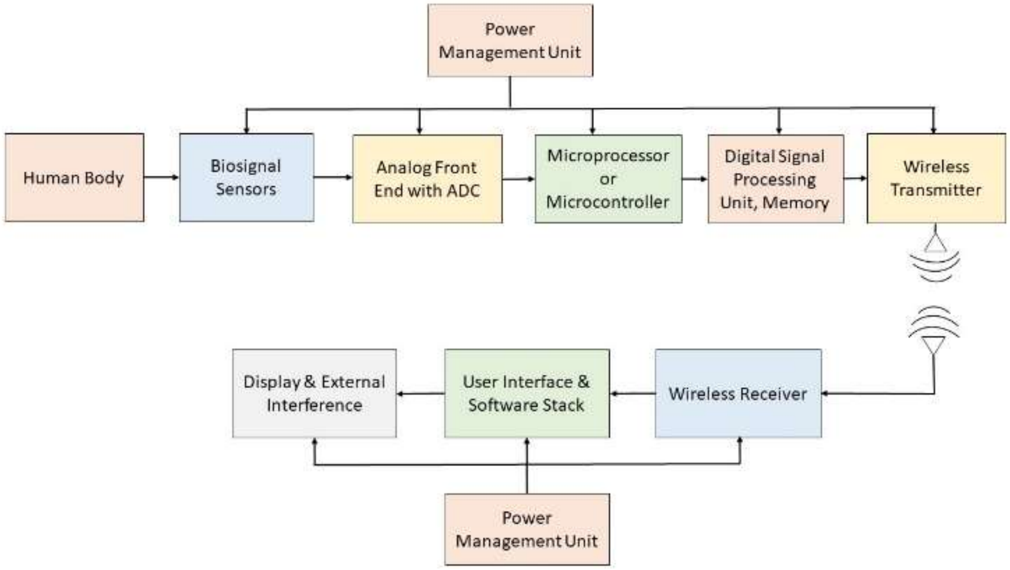


Figure 2.3 General architecture of a Microprocessor Based System.

2.5.3 System on Chip (SoC)

A System on Chip (SoC)-based wireless Bio DAQ system integrates all critical components, such as analog front end circuits, digital signal processing units, wireless communication modules, and power management circuits, onto a single chip. In certain designs, the wireless communication and power management modules are housed separately from the SoC chip [52, 55]. This high level of integration provides multiple benefits, including reduced system complexity, a smaller physical footprint, lower power consumption, and potentially lower production costs. SoC-based systems are particularly well-suited for implantable biomedical devices, where space, power efficiency, and performance are key priorities. As a result of these advantages, numerous SoC-based systems have been developed [18, 42, 43, 52, 53, 55].

The architecture of a System on Chip (SoC)-based system closely resembles that of a microprocessor-based system. It comprises biosignal sensors, an analog signal conditioning unit, an A/D converter, a microprocessor or microcontroller, a Digital Signal Processing (DSP) unit, a wireless transceiver, a user interface and display, and a power management unit. A general representation of this architecture is illustrated in Figure 2.4 [17].

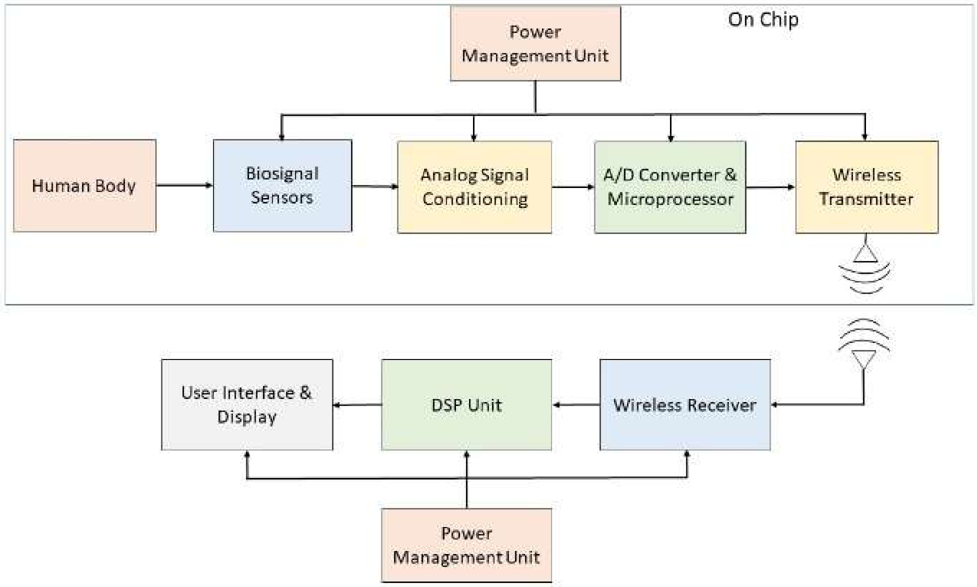


Figure 2.4 General architecture of a System on Chip (SoC) based System.

In addition to the approaches mentioned earlier, hybrid systems combining System on Chip (SoC) solutions, analog front ends (AFE), and transmitter and receiver modules are also being developed [50]. These systems leverage the advantages of multiple design approaches, offering improved functionality, performance, and flexibility. A comparison of the merits and demerits of each design approach is provided in Table 2.3, highlighting their unique characteristics and suitability for various applications.

Table 2.3 Advantages and limitations of different design approaches

Design approach	**Advantages**	**Limitations**
Fully analog system	i. Low power consumption. ii. Real time signal fidelity - Analog signals maintain their fidelity throughout the system without the need for digitization, preserving the original characteristics of the biosignals. ii. Reduced Complexity - Fully analog systems often have simpler architectures compared to their digital counterparts, leading to lower design complexity and potentially lower costs. iv. Lower Latency. v. Compatible with Analog Sensors.	i. Limited signal processing capabilities. ii. Vulnerable to external interferences. ii. Customizing or modifying signal processing algorithms can be more challenging in fully analog systems compared to digital systems. iv. Analog signals offer less flexibility for manipulation and post-processing. v. Scalability challenges.

Microprocessor based system	i. Microprocessors enable advanced digital signal processing techniques, allowing for real time filtering, analysis, and feature extraction of biosignals. ii. Easy customization and adaptation to different biosignal types and applications. ii. Can integrate multiple functions, such as signal processing, wireless communication, and user interfaces, into a single platform. iv. Remote monitoring capability. v. Improved data transmission efficiency.	i. Microprocessor based systems tend to consume more power compared to fully analog systems. ii. The complexity of microprocessor based systems increases design complexity and production costs compared to simpler analog systems. ii. The additional processing involved in digitizing and processing biosignals can introduce latency, which may be undesirable for real time applications requiring immediate feedback. iv. Wireless communication in microprocessor based systems may be susceptible to interference from other electronic devices, leading to potential data corruption or loss.
SoC based system	i. All necessary components are integrated onto a single chip, leading to reduced system complexity, smaller footprint, and potentially lower production costs. ii. SoC based systems offer compact form factors, making them suitable for portable, wearable, and implantable biomedical devices where space is limited. ii. Lower power consumption. iv. SoC architectures enable optimization of signal processing algorithms and wireless communication protocols, leading to improved performance and efficiency.	i. Integration onto a single chip may limit flexibility for customization and expansion. ii. Designing and manufacturing SoC based systems require specialized expertise and resources, which may pose challenges for smaller companies or developers. ii. A failure in any component of the SoC could render the entire system inoperable, posing reliability concerns, especially in critical applications. iv. Upgrading or modifying SoC based systems may be more challenging compared to modular designs, potentially requiring redesign and retooling.

2.6 Research Gap

Majority of the systems available in the market are wired systems. Wired systems have different limitations. It is very uncomfortable for the subjects due to complexity of wires. Although wireless Bio DAQ systems has garnered significant attention from researchers and developers, it still faces several limitations and challenges. These include the high computational power required for advanced filtering techniques, memory and processing limitations of Arduino or other small development boards, and the difficulty in maintaining high signal fidelity. Additionally, the accurate evaluation of measured signals and their reliable interpretation to identify potential medical issues remain critical challenges in this field.

Most commercially available systems are tailored for specific signals such as ECG, EEG, or EMG. The amplifier gains and filter frequencies in these systems are optimized for the targeted signals, making it challenging to use a single device for acquiring other types of signals. For example, the device and amplifier is specifically designed for acquiring ECG signals cannot be used for acquiring EMG signals. This restricts the versatility of the system.

An integrated stimulator allows controlled delivery of stimuli (e.g., electrical pulse) to evoke physiological responses. This capability is critical for diagnostic applications such as nerve conduction studies and evoked potential testing, where analyzing the body's response to stimuli helps identify abnormalities. Most of the systems available in the market do not have integrated stimulator. In some systems, they use standalone stimulator, and these stimulators are designed using oscillator circuits and transformers, which fail to generate properly charge-balanced pulses. Such waveforms can result in tissue damage due to the continuous flow of direct current. When an electrode transmits current through a conductive solution, chemical reactions occur at the interface. Prolonged application of high voltage can induce strong faradic currents, leading to, gas formation, electrolysis, pH shifts, electrode corrosion, and tissue damage [14, 15]. Ensuring properly charge-balanced waveforms is essential to prevent these adverse effects and maintain patient safety over extended use, is a major challenge.

Addressing these research gaps is crucial for the advancement of wireless Bio DAQ technology. Future research should focus on developing wireless Bio DAQ systems which should not be signal specific like only ECG, EMG, EEG etc, and cater wide range of signals. It should have an integrated stimulator and stimulator should produce truly charge-balanced waveforms. Stimulator should understand and mitigate the chemical effects at the electrode-tissue interface, reduce adverse effects of stimulation and maintain patient safety over extended use. By overcoming these challenges, wireless Bio DAQ systems can become more effective, safe, and user-friendly, thereby improving the quality of life for patients.

2.7 Conclusion

The emergence of Bio DAQ systems has transformed medical and research practices by providing specialized tools to capture and amplify electrical signals generated by the body. While wired systems have traditionally dominated the field, they pose challenges for long-term patient monitoring and animal studies. Wireless Bio DAQ systems address these limitations, offering greater flexibility and comfort. These advancements have led to the development of various wireless biosignal acquisition technologies, including fully analog systems, microprocessor-based designs, system-on-chip (SoC) architectures, and hybrid systems that combine SoC, analog front-end (AFE), and transmitter/receiver modules. Despite the wide range of available wireless biosignal acquisition devices, a comprehensive review detailing their types, applications, and underlying technologies remains absent. Additionally, we have explored the integration of stimulators into biopotential devices, which deliver electrical impulses based on real-time neuronal activities.

This chapter tried to fill the existing gap by offering a thorough review of the latest wireless Bio DAQ systems. It delves into their applications, signal acquisition methodologies, and wireless technologies, highlighting key aspects such as signal processing and noise reduction techniques. By addressing the developmental challenges and comparing the advantages of wireless systems over traditional wired setups, this systematic review provides valuable insights for researchers, developers, and healthcare professionals. It serves as an essential resource to understand the current state of wireless biosignal acquisition devices and their potential to revolutionize healthcare through continuous and remote physiological monitoring.

The findings also emphasized the need for future research to focus on improving signal processing, enhancing accuracy, exploring new applications, developing wireless Bio DAQ systems which should not be signal specific, integration of stimulator which focus on reducing adverse effects of stimulation and maintain patient safety over extended use.

CHAPTER - 3

Circuit Design and Development of Bio DAQ System

Chapter 3

Circuit Design and Development of Bio DAQ System

3.1 Introduction

Biopotential data acquisition system (Bio DAQ) is a specialized tools utilized in medical and research domains to capture and amplify the body's electrical signals. These systems play a vital role in obtaining precise and high-quality data from various physiological sources. These systems are integral in biomedical applications, capturing signals such as electrocardiograms (ECG), electroencephalograms (EEG), and electromyograms (EMG).

Designing of wireless Bio DAQ circuit is very critical and consists of several processes. The process begins with specialized sensors or electrodes that detect biopotential signals from the skin or underlying tissues. These weak signals, typically in the microvolt to millivolt range, are then amplified using precision amplifiers to ensure they are strong enough for analysis. Noise filtering mechanisms are applied to eliminate interference from environmental and physiological artifacts, ensuring signal clarity. The filtered signals are converted into digital form using Analog-to-Digital Converters (ADCs), enabling further processing, and feeding to the microcontroller. Then it is integrated with wireless communication, real-time monitoring capabilities, and advanced signal processing algorithms to enhance diagnostic accuracy and enable remote healthcare applications and storage.

In this chapter we will describe the methods adopted in designing the circuit of wireless Bio DAQ system. The chapter starts with the general challenge and targeted objective of the design. This will be followed by methods of development of several subsystems like Analog Front End (AFE), Microcontroller Unit (MCU), stimulator unit, wireless system, power supply, user interface and firmware development. It will describe the different stages of development like from initial schematic design to the final PCB layout and breadboard implementation of the circuit.

3.2 Challenges

One of the primary challenges in real-time monitoring of biopotential signals lies in the development of a wireless module that can seamlessly integrate with the human body. This module must accurately sense, amplify, and transmit biopotential signals that typically range from tens of microvolts to several millivolts. The sensitivity required to capture such weak signals without distortion demands advanced sensor technologies and precision amplifiers. Additionally, the module must be robust enough to maintain signal integrity despite potential interference from environmental noise, movement artifacts, and other physiological variations.

Another critical aspect is the compact size of the module. Since these devices are often designed for wearable applications, their size must be minimized to ensure comfort and unobtrusiveness for the user. This is also an important aspect for animal studies. Compactness not only enhances user experience but also opens up possibilities for broader applications, including long-term health monitoring, athletic performance tracking, and research studies. The miniaturization process, however, poses significant engineering challenges, as it requires the integration of multiple functionalities—such as sensing, amplification, data processing, and wireless communication—into a single, small form factor without compromising performance.

Equally important is the need for low power consumption to ensure sufficient battery life. Real-time physiological monitoring often requires continuous operation over extended periods, making energy efficiency a paramount concern. Power optimization strategies must be employed at every stage, from the sensing and amplification processes to data transmission and wireless communication.

Compliance with regulatory standards and obtaining ethical clearance for clinical trials add another layer of complexity. The device must meet all safety and efficacy requirements, which involves rigorous testing and documentation.

Cost considerations also play a crucial role. Balancing advanced features with affordability is necessary to make the wireless Bio DAQ system accessible without compromising quality or safety. Ensuring the device's durability and minimal maintenance needs reduces long-term costs for patients and healthcare providers.

Finally, the implementation of wireless Bio DAQ system must also consider the clinical environment and the practical aspects of device use. These systems need to be user-friendly, easy to set up, and reliable in real-world conditions. Healthcare providers must be able to quickly and accurately calibrate and adjust the devices for each patient, ensuring optimal performance without requiring extensive technical expertise. Balancing these practical considerations with the need for advanced signal conditioning presents a significant challenge in the development and deployment of effective wireless Bio DAQ system.

3.3 Objective

To address these existing challenges, we have developed a new novel design approach of a compact, low-cost, wireless, 16-channel wireless Bio DAQ system.

There are several novel and flexible design approaches were incorporated in the design like:-

(1) It has user selectable digital filter in each channel based on the signal frequencies like EOG, EEG, ECG, and EMG. The same system is capable of acquiring different signals simultaneously like EMG with ECG, EEG etc.

(2) It has variable gain and configurable analog bandpass filter. User can upgrade the filter of the system to any frequency band by placing resistance and capacitor in a predefined footprint in the PCB.

(3) It has 4 reference electrode drive amplifier (DRL). It is capable of acquiring biopotential signal from 4 patients simultaneously.

(4) The system can acquire signal from both two-electrode system as well as three-electrode configuration.

(5) It has integrated stimulator with charge-balanced, trapezoidal, biphasic stimulus output with near zero DC level. The stimulator parameters like pulse duration and frequency of the stimulus can also be controlled by the user.

3.4 Methods

To ensure accurate interpretation of various biosignals, several key parameters were taken into account, including the number of channels, channel resolution, sampling rate, configurable options, future upgradability, error-free data transfer, and energy efficiency. The detailed specifications of the developed system are provided in Table 3.1.

Table 3.1. Specification of the developed wireless Bio DAQ System

Sl No	Parameter	Specification
1	Number of Channels	16
2	Resolution of each channel	10 bit
3	Sampling rate	75Hz to 500Hz
4	Gain	Variable
5	Input Impedance	$10^{12}\Omega$
6	Electrode Configuration	both 2 electrode & 3 electrode
7	Data Transfer	Wirelessly using Wi-Fi with a range of 40m
8	Digital Filter Method	4^{th} order IIR band pass filter with user selectable frequency based on EMG, ECG, EEG, EOG.
9	Integrated Electrical Stimulator	Biphasic, charge-balanced, trapezoidal, stimulus output with nearzero DC level and user selectable frequency and pulse duration of the stimulus
10	Dimension	26cmX21cm(including battery pack)
11	Weight	400g
12	Battery	7.4V, 2200mAh, Li-ion battery

3.4.1 Block Diagram

The system consists of several subsystems, including the Analog Front End (AFE), Microcontroller Unit, Stimulator Module, Wireless Module, Display, and Power Supply unit. The block diagram of the developed system is shown in Figure 3.1. Design and development of each subsystem has been described in the next section.

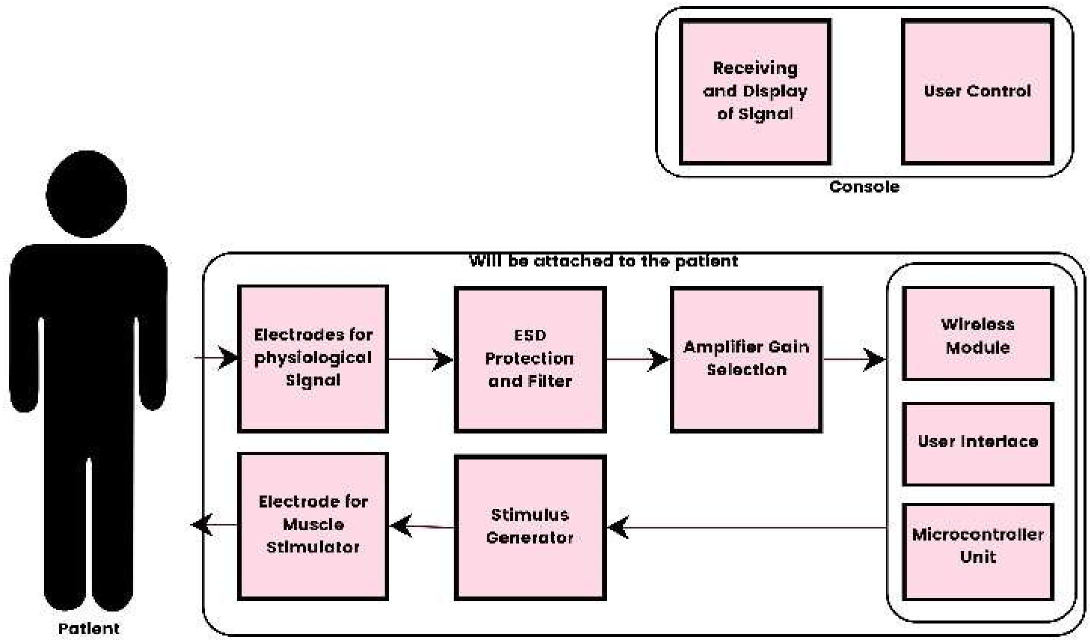


Figure 3.1 Block Diagram of Wireless Bio DAQ System.

3.4.2 Analog Front End (AFE)

Analog front end (AFE) receives raw signals from electrode. It consists of low pass filter (LPF), instrumentation amplifier (IA), configurable band pass filter (BPF), right leg drive (DRL) circuit, power supply filter and electrode reference selection circuit.

3.4.2.1 Low Pass Filter (LPF): Raw signals received from the electrode initially passed through a R-C low pass filter (LPF). This is placed in between positive (IN+) and negative (IN-) input signals received from electrode. The filter has a cutoff frequency of 7.284KHz to eleminate high frequency noise.

3.4.2.2 Instrumentation Amplifier (IA): It is then followed by an instrumentation amplifier (IA). We used TL084 operational amplifiers (Texas Instruments, USA) in designing the amplifiers because it has several advantage for application in biosignal amplification. The advantages of TL084 is mentioned below:

(i) ***Low Noise Performance:*** The TL084 is designed with low input noise (Vn = 18 nV/√Hz (typ) at f = 1 kHz), which is critical for amplifying bio-signals such as EEG, ECG, and EMG, as these signals are typically weak and easily affected by noise [66].

(ii) ***High Input Impedance:*** With a high input impedance, the TL084 minimizes loading effects on the signal source, preserving the integrity of bio-signals, especially when interfaced with high-impedance biological electrodes.

(iii) ***Low Power Consumption:*** The TL084 operates efficiently with low power consumption (940 µA/ch), making it ideal for portable and battery-powered biomedical devices, where energy efficiency is essential [66].

(iv) ***Wide Supply Voltage Range:*** It supports a wide range of supply voltages (±2.25V to ±20V), offering flexibility in system design and compatibility with various power supply configurations [66].

(v) ***High Slew Rate:*** The amplifier's high slew rate (20 V/μs) ensures fast response to changes in bio-signals, making it suitable for real-time monitoring and applications that require rapid signal processing [66].

(vi) ***Quad Amplifier Package:*** The TL084 integrates four operational amplifiers in a single package, reducing the overall footprint of the circuit. This compactness is particularly beneficial for designing space-constrained medical and wearable devices.

(vii) ***Excellent Linearity:*** Its superior linearity ensures accurate amplification of bio-signals without introducing significant distortion, crucial for maintaining the fidelity of physiological data.

(viii) ***Thermal Stability:*** The TL084 exhibits stable performance across a wide temperature range, ensuring reliability in varying environmental conditions, which is important for both clinical and field applications.

(ix) ***Cost-Effectiveness:*** As a widely available and affordable component, the TL084 offers an economical solution for developing high-performance bio-signal amplification systems.

(x) ***Low Offset Voltage:*** The low offset voltage of 1mV characteristic minimizes DC biasing issues, which is critical for accurate amplification of low-frequency bio-signals such as those from ECG and EEG. It also has a low offset voltage drift: 2 μV/°C [66].

We have used a variable resistor in the feedback circuit which introduced variable gain in the IA circuit. The schematic of the IA circuit is shown in Figure 3.2.

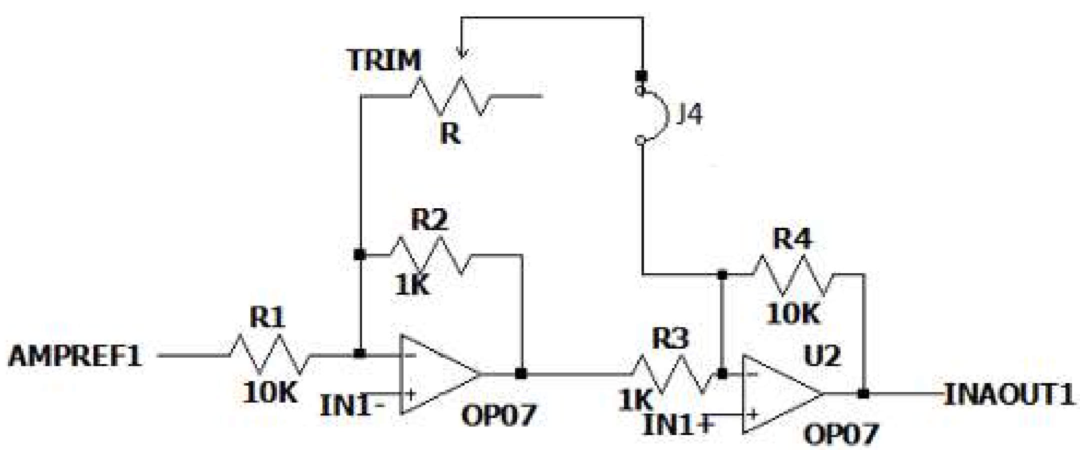


Figure 3.2 Schematic of Instrumentation Amplifier (IA) circuit with variable gain at AFE.

3.4.2.3 Band Pass Filter (BPF): It is then passed through a configurable band pass filter (BPF). We used TL084 operational amplifiers (Texas Instruments, USA) in designing the filter because of its above mentioned advantages. It has configurable options, one with a standard frequency range of 0.5Hz – 3.38kHz and have a gain of 1000. But user can configure the system by any frequency band by placing resistance (BPFC_R) and capacitor (BPFC_C) in a predefined footprint in the PCB throgh a jumper. The jumper will bypass the standard frequency setting and select the user defined frequency setting. The schematic of the BPF circuit is shown in Figure 3.3.

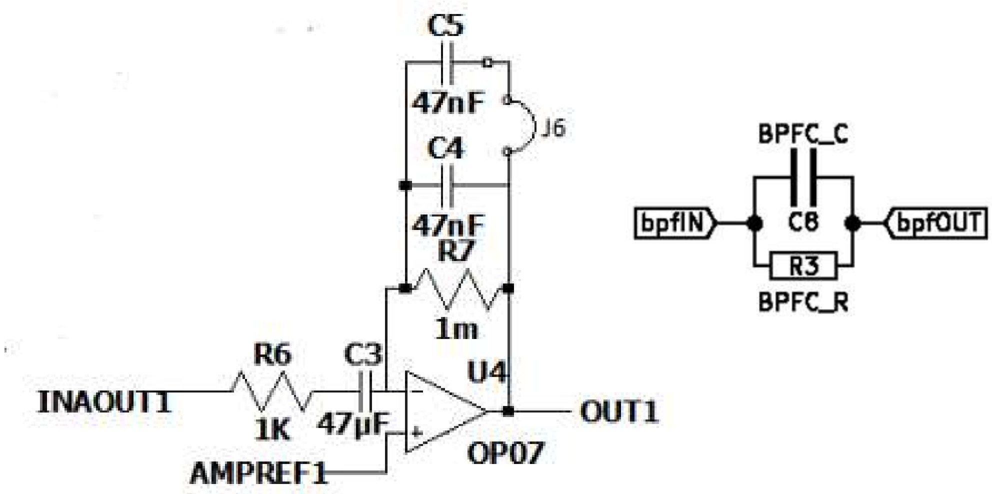


Figure 3.3 Schematic of Band Pass Filter (BPF) circuit at AFE.

3.4.2.4 Right Leg Drive (DRL): The Right Leg Drive (DRL) circuit is a crucial component in bio-signal amplifiers. It enhances the quality and reliability of the acquired signals. The primary significance of the DRL circuit lies in its ability to reduce common-mode interference, such as noise from power lines or electromagnetic sources, which can distort the low-amplitude bio-signals. By actively driving the subject's right leg or a reference point with a feedback signal, the DRL circuit dynamically cancels out common-mode voltages across the electrodes, effectively improving the signal-to-noise ratio.

Another critical role of the DRL circuit is minimizing baseline drift caused by electrode polarization or skin impedance variations. This stabilization ensures that the amplifier's input stage operates within its optimal range, preventing signal saturation and maintaining accurate measurements. Additionally, the DRL circuit improves patient safety by limiting the current delivered to the body in case of faults or malfunction, thereby adhering to stringent medical safety standards.

The circuit also allows for higher input impedance in the bio-signal amplifier, which reduces signal loading and distortion. Its implementation is particularly significant in environments with high ambient noise, such as hospitals or industrial settings, ensuring consistent and reliable monitoring of physiological signals. Overall, the DRL circuit is essential for achieving clean, high-quality bio-signal acquisition, enabling accurate diagnosis and research outcomes. We have incorporated four right leg drive (DRL) circuit for simultaneously acquiring signals from upto four subjects or patients. We used TL084 operational amplifiers (Texas Instruments, USA) in designing the DRL circuit because of its advantages mentioned in para 3.4.2.2. The schematic of a single channel DRL circuit is shown in Figure 3.4.

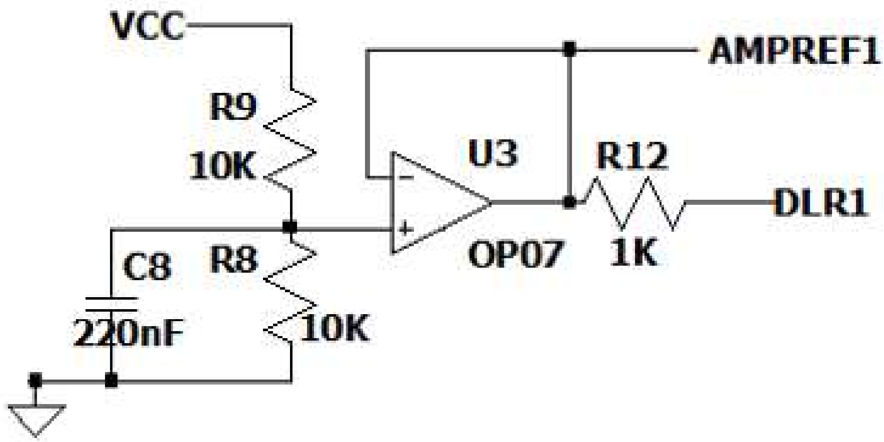


Figure 3.4 Schematic of single channel Right Leg Drive (DRL) circuit at AFE.

3.4.2.5 Power Supply Filtering Circuit: We connected two capacitors of 100nF and 4.7µF in parallel between Vcc and ground to remove power line interferences. This parallel capacitor configuration is highly effective for reducing power line interference over a broad frequency range. It ensures a clean and stable power supply for sensitive analog or digital circuitry, which is especially critical in systems like bio-signal amplifiers where even minor noise can compromise signal fidelity.

100nF Capacitor (C1) is a high-frequency filter. It effectively suppresses high-frequency noise and transient spikes, such as those caused by electromagnetic interference (EMI) or switching in digital circuits. Its small capacitance ensures a low reactance at high frequencies, making it efficient for noise above a few hundred kHz.

4.7µF Capacitor (C2) is a low-frequency filter. It stabilizes the power supply by filtering out lower-frequency noise, such as ripple voltage from the rectifier circuit in power supplies. Its larger capacitance provides sufficient energy storage to compensate for variations in the power line, maintaining a steady Vcc. The schematic of power line filtering circuit is shown in Figure 3.5.

)LJXUH 6FKHPDWLF RI SRZHU OLQH ILOWHULQJ FLUFXLW

(OHFWURGH &RQILJXUDWLRQ :H KDYH LQFRUSRUDWHG HOHFWURGH VHOHFWRU VR WKDW WKH V\VWHP FDQ EH XVHG IRU DFTXL HOHFWURGH DQG HOHFWURGH FRQILJXUDWLRQ 7KH HOH VLPSOH QRQ FULWLFDO DSSOLFDWLRQV ZKHUH HDVH RI XV HOHFWURGH FRQILJXUDWLRQ LV HVVHQWLDO IRU DSSOLFDW UHMHFWLRQ DQG GLDJQRVWLF DFFXUDF\ PDNLQJ LW WK HQYLURQPHQWV *HQHUDOO\ HOHFWURGH FRQILJXUDWLRQ HOHFWURGH FRQILJXUDWLRQ $ FRPSDULVRQ WDEOH RI H LV VKRZQ LQ 7DEOH

7DEOH &RPSDULVRQ RI HOHFWURGH DQG HOHFWURGH F

)HDWXUH	HOHFWURGH	FRQILJXUDWLRQ	HOHF
1XPEHU RI (OHFWURGHV			
1RLVH 5HMHFWLRQ	/RZ	+LJK UHMHFWLRQ	GXH WR FR
6LJQDO 4XDOLW\	0RGHUDWH		+LJK
$SSOLFDWLRQV	:HDUDEOHV (0*	&OLQLFDO GLDJQRVWLFV (0*	DGYDQFHG
(DVH RI 8VH	9HU\ HDV\		0RGHUDWHO\ FRPS
0RWLRQ 6HQVLWLYLW\	$UWLIDFW +LJK	/RZ ZLWK SUR	SHU JURXQGL

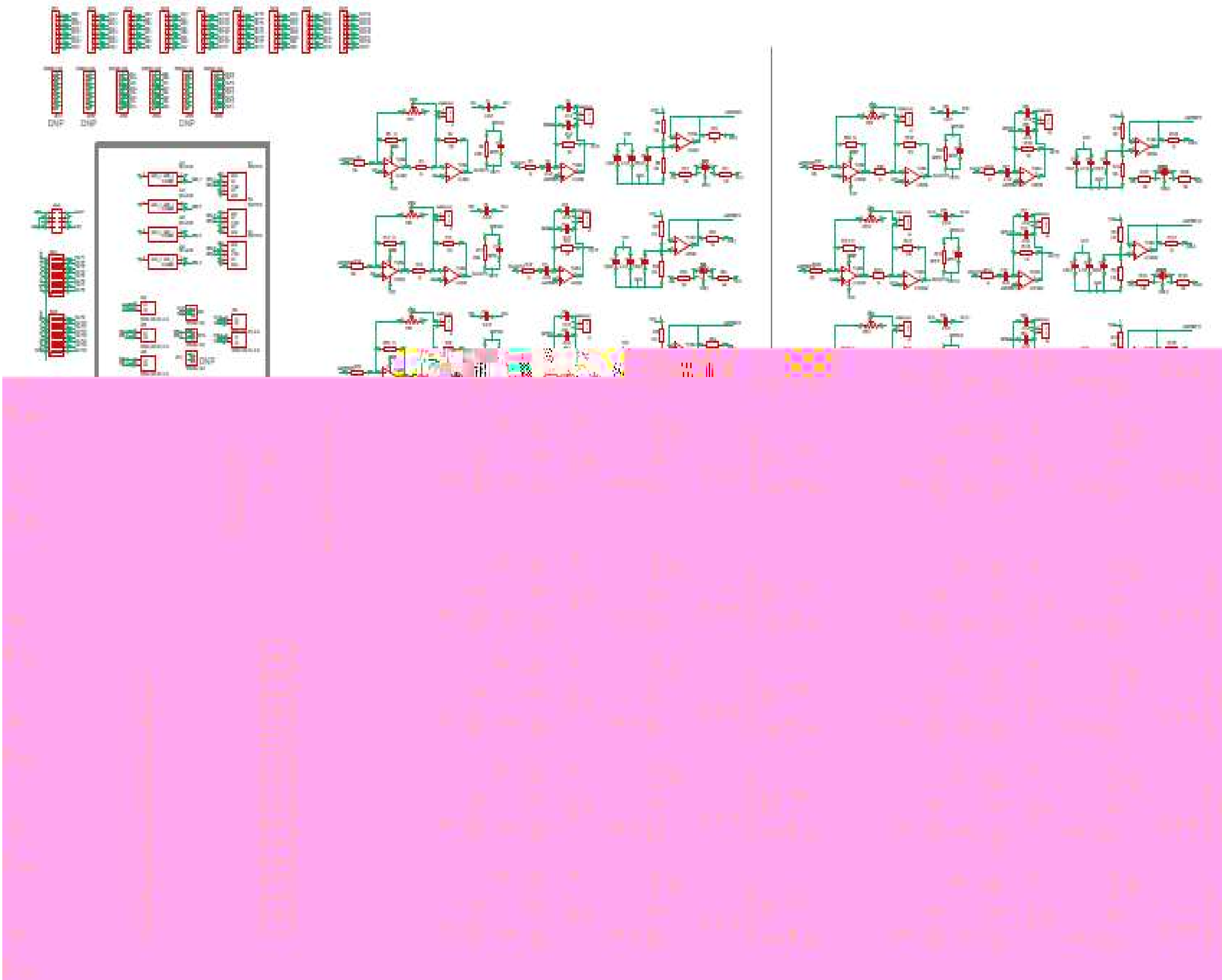


Figure 3.8 Schematic of 16-channel Analog Front End (AFE).

3.4.3 Microcontroller Unit (MCU)

We have chosen and incorporated ATmega2560 microcontroller through Arduino MEGA development board as it has 16 analog input channels which is a crucial requirement for our system design. ATmega2560 microcontroller has several advantages mentioned below:

(i) ***Multiple Analog Input Channels:*** The ATmega2560 microcontroller features 16 analog input channels, allowing it to simultaneously interface with multiple bio-signal sources, such as ECG, EEG, or EMG signals. This capability makes it ideal for multi-channel bio-signal acquisition systems [67].

(ii) ***Large Flash Memory:*** With 256KB of flash memory, the ATmega2560 provides sufficient storage for complex firmware, enabling the inclusion of advanced features such as signal processing, filtering, and data compression algorithms [67].

(iii) ***Low Power Consumption:*** The microcontroller's energy-efficient design ensures minimal power usage, making it suitable for portable or wearable bio-signal devices that rely on battery power. Power consumption in Active Mode: 1MHz, 1.8V: 500µA [67].

(iv) ***Versatile Communication Interfaces:*** It supports multiple communication protocols, including SPI, UART, and I2C, which facilitate seamless integration with peripheral devices like analog front ends, wireless transmitters, and external storage units. This versatility ensures compatibility with various components in bio-signal amplification systems.

(v) ***High Processing Speed:*** The ATmega2560 operates at clock speeds of up to 16 MHz, providing sufficient computational power to handle real-time bio-signal processing tasks without significant delays [67].

(vi) ***Cost-Effectiveness:*** As a widely used microcontroller, the ATmega2560 offers an affordable solution without compromising performance, making it accessible for both research and commercial applications in bio-signal amplification.

(vii) ***Built-In ADC:*** The integrated 10-bit Analog-to-Digital Converter (ADC) ensures precise conversion of analog bio-signals into digital format for further processing. The ADC's resolution is adequate for capturing subtle variations in low-amplitude bio-signals.

(viii) ***Customizable GPIOs:*** With numerous general-purpose input/output (GPIO) pins, the ATmega2560 can be configured to control additional components such as LEDs, relays, or displays, enhancing the functionality of the bio-signal device.

(ix) ***Interrupt Support:*** The microcontroller's robust interrupt system allows it to prioritize and handle critical tasks efficiently, such as responding to bio-signal events or managing data communication.

(x) ***Wide Community Support:*** As a popular microcontroller, the ATmega2560 benefits from extensive documentation, open-source libraries, and community support, simplifying development and troubleshooting for bio-signal applications.

(xi) ***Compact Size and Flexibility:*** Its small form factor and flexible architecture make it suitable for integration into compact bio-signal amplification devices, especially for wearable or portable designs.

By leveraging these advantages, the ATmega2560 microcontroller is a powerful and reliable choice for bio-signal amplification devices, enabling accurate signal acquisition, efficient processing, and seamless communication in a cost-effective and energy-efficient package. The pinout diagram of ATmega2560 microcontroller in Arduino MEGA development board is shown in Figure 3.9.

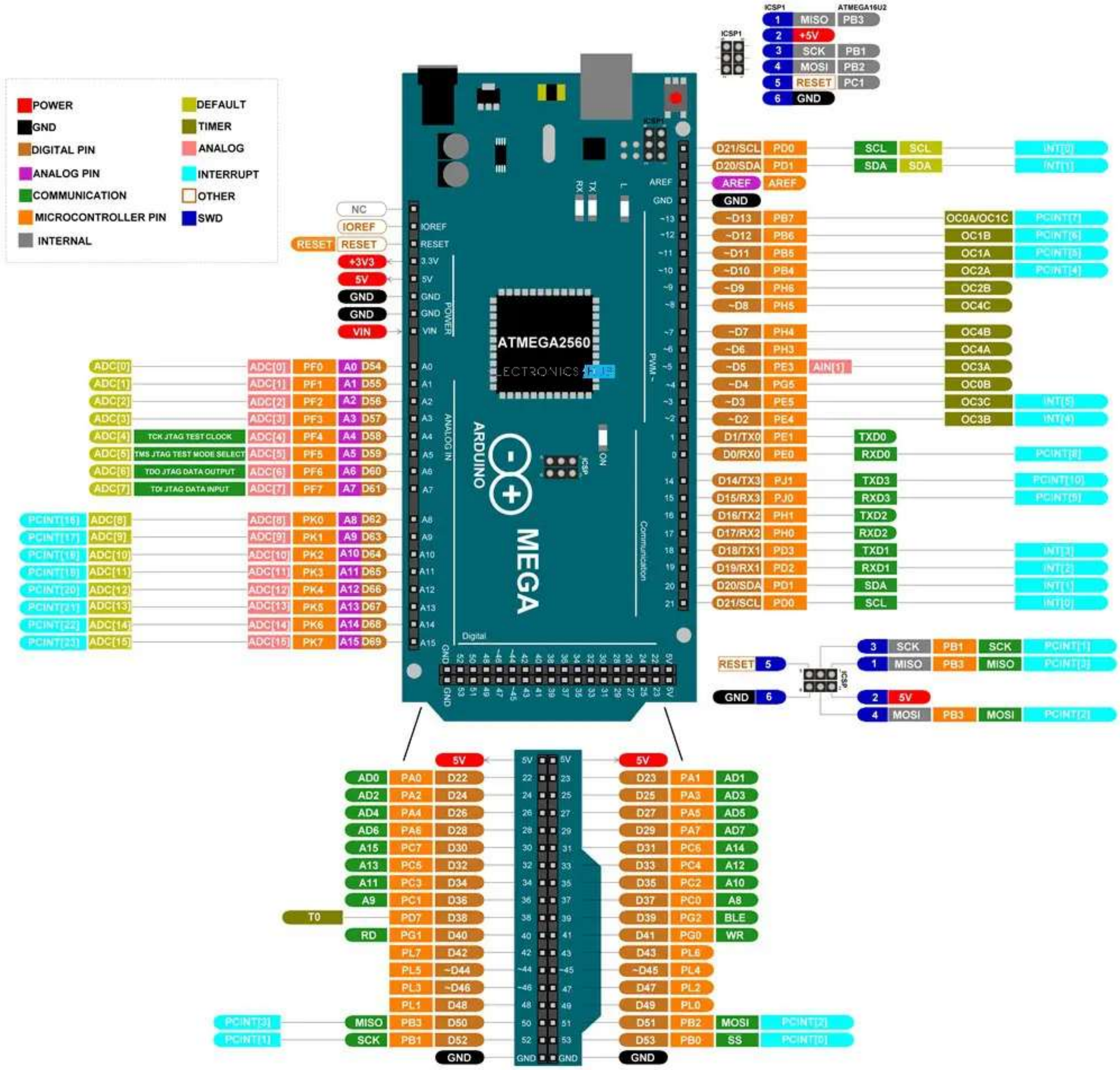


Figure 3.9 Pinout diagram of ATmega2560 microcontroller in Arduino MEGA development board[68].

The system design incorporates 16 analog signals originating from the Analog Front End (AFE), each routed to a corresponding analog input of the microcontroller through a DIP switch. This switch-based configuration allows for selective channel usage, ensuring that any unused channels are securely grounded. By grounding unused channels, the system effectively prevents them from being left in a floating state, which could otherwise introduce noise interference and degrade the overall signal quality. This grounding mechanism is critical for maintaining the integrity of the biosignal data and ensuring accurate measurements.

The microcontroller is tasked with reading the biosignal data from the measurement block via the Serial Peripheral Interface (SPI). SPI is a high-speed, synchronous communication protocol that ensures efficient data transfer between the AFE and the microcontroller. This setup allows the microcontroller to acquire data reliably and in real time, supporting applications that demand precision and low latency. By employing SPI, the system minimizes the risk of data loss or corruption during signal acquisition, further enhancing the reliability of the biosignal acquisition process.

Once the biosignal data is collected and processed by the microcontroller, it is transmitted to the wireless transmitter using the Universal Asynchronous Receiver-Transmitter (UART) protocol. UART provides a straightforward and effective means of asynchronous communication between the microcontroller and the wireless transmitter. This step is essential for enabling the wireless transmission of biosignal data to external systems, such as a computer or a mobile device, for further analysis and display. By leveraging UART, the system ensures seamless integration between the microcontroller and the wireless module, enabling efficient and reliable data communication in a compact and power-efficient manner.

3.4.4 Wireless Transmitter (Tx)

3.4.4.1 Design Using NRF24L01 2.4GHz FSK Module:

Initially we have designed our wireless transmitter and receiver system using M177 NRF24L01 2.4GHz Wireless Transceiver Module, which provides an effective range of approximately 40-60 meters. This range offers excellent flexibility for wireless communication, making it a critical factor in selecting this module for our application. The nRF24L01 is a highly efficient, integrated transceiver IC specifically designed for very low-power operations. It functions within the globally allocated 2.4 GHz Industrial, Scientific, and Medical (ISM) frequency band, which is designated for unlicensed low-power devices, ensuring broad compatibility and minimal interference.

The module utilizes Gaussian Frequency-Shift Keying (GFSK) modulation for robust and efficient data transmission. One of its notable features is its configurable data transfer rates, providing options to operate at 250 kbps, 1 Mbps, or 2 Mbps, catering to diverse requirements for speed and data integrity. With peak RX/TX currents below 14 mA and an ultra-low-power standby mode consuming less than 1 µA, the module is optimized for energy efficiency. This low power consumption extends the operational lifespan of battery-powered devices, a crucial advantage in portable and remote monitoring applications. Additionally, its ability to operate within a supply voltage range of 1.9 to 3.6 V further enhances its adaptability to various power supply scenarios.

In our setup, the M177 NRF24L01 module is seamlessly integrated with an ATmega2560 microcontroller on the transmitter side and ATmega328 microcontroller on the receiver side. The microcontroller communicates with the transceiver using the Serial Peripheral Interface (SPI) protocol, efficiently handling the received biosignal data. This data is subsequently transmitted to a computer or processing unit for analysis, ensuring reliable and consistent data handling. This configuration, combining the advanced features of the NRF24L01 with the processing capabilities of the ATmega microcontroller, provides a power-efficient, flexible, and robust solution for wireless biosignal transmission. The pinout diagram of M177 NRF24L01 2.4GHz Wireless Transceiver Module is shown in Figure 3.10.

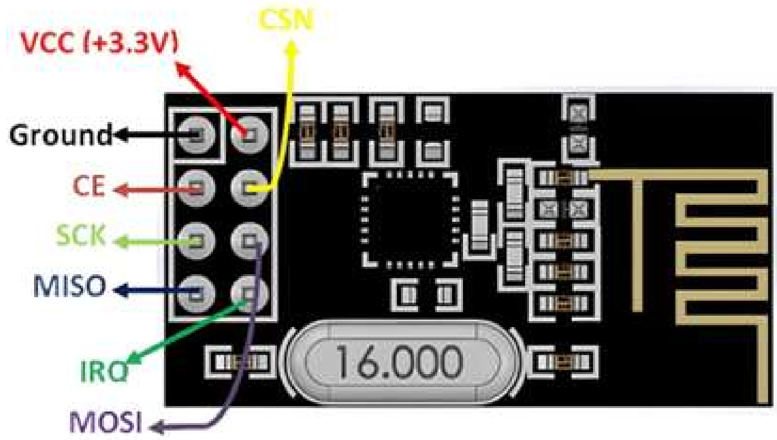


Figure 3.10 Pinout diagram of M177 NRF24L01 2.4GHz Wireless Transceiver Module [69].

One of the major limitations of NRF24L01 module is that it requires external components like microcontrollers to handle protocols and manage data processing. This system cannot be integrated to any computer or network without having any receiver module. Due to this we have to design a receiver module incorporating of NRF24L01 2.4GHz Wireless Transceiver Module with ATmega328 microcontroller for implementing the wireless Bio DAQ system. However the system works properly and successfully received biopotential signals.

3.4.4.2 Design Using ESP 8266 Wi-Fi Module:

To address the above mentioned limitations of NRF24L01 module, we have chosen ESP 8266 Wi-Fi module for our wireless transmitter design as it does not require any external hardware like microcontroller at the receiver end. It is very easily connected to any laptop or device which has inbuilt Wi-Fi facilities. Apart from these, ESP 8266 Wi-Fi Module has several advantages over NRF24L01 module which is described below:

(i) ***Internet Connectivity:*** The ESP8266 allows direct connection to wireless networks and enabling internet-based communication.
The NRF24L01 lacks internet connectivity and is limited to local device-to-device communication.

(ii) ***Standalone Operation:*** The ESP8266 features an integrated microcontroller, allowing it to process data, run programs, and operate as a standalone device.
The NRF24L01 requires an external microcontroller for operation, increasing hardware complexity.

(iii) ***Higher Data Rate:*** The ESP8266 supports data rates exceeding 50 Mbps (802.11n standard), ideal for high-bandwidth applications.

The NRF24L01 is limited to a maximum of 2 Mbps, which may not suffice for some data-intensive tasks.

(iv) ***Extended Range:*** The ESP8266 can achieve communication ranges up to 300 meters in line of sight, depending on the router and environment.

The NRF24L01 typically offers shorter ranges, around 50-100 meters, even in optimal conditions.

(v) ***Enhanced Security:*** The ESP8266 supports robust security protocols like WPA/WPA2 encryption, ensuring secure data transmission over wireless networks.

The NRF24L01 provides basic security through channel hopping but lacks advanced encryption.

(vi) ***Scalability and IoT Integration:*** The ESP8266 easily integrates with IoT platforms and cloud services, enabling scalable systems for remote monitoring and control.

The NRF24L01 is more suited for limited, localized communication and lacks cloud integration capabilities.

(vii) ***Ease of Development:*** The ESP8266 has extensive support from a well-established ecosystem, including libraries, documentation, and community resources, simplifying development.

The NRF24L01, while supported, requires custom protocols and more complex programming.

(viii) ***Advanced Communication Protocols:*** The ESP8266 supports popular protocols such as HTTP, MQTT, and WebSocket, making it ideal for modern IoT applications.

The NRF24L01 requires manual implementation of custom protocols, which can increase development time.

(ix) ***Increased Device Compatibility:*** The ESP8266 works seamlessly with existing Wi-Fi networks, enabling direct communication with smartphones, laptops, and routers.

The NRF24L01 requires additional modules to interface with standard Wi-Fi devices.

(x) ***Fewer Components Required:*** The ESP8266 combines a transceiver and microcontroller in a single module, reducing the need for additional components.

The NRF24L01 always requires an external microcontroller, adding to the system's complexity and cost.

(xi) ***Higher Throughput:*** For applications requiring large amounts of data to be transferred quickly, such as biopotential signal data, the ESP8266 performs significantly better than the NRF24L01.

The ESP8266 Wi-Fi module is more versatile, powerful, and scalable compared to the NRF24L01, particularly for applications requiring internet access, high data rates, or cloud connectivity. While the NRF24L01 excels in low-power, short-range, and cost-sensitive tasks, the ESP8266 is the superior choice for modern IoT and biomedical systems applications. The data from the ATmega8260 microcontroller is fed to ESP 8266 wifi module and then it transmit the data using TCP/IP protocols. The pinout diagram of ESP 8266 Wi-Fi module is shown in Figure 3.11.

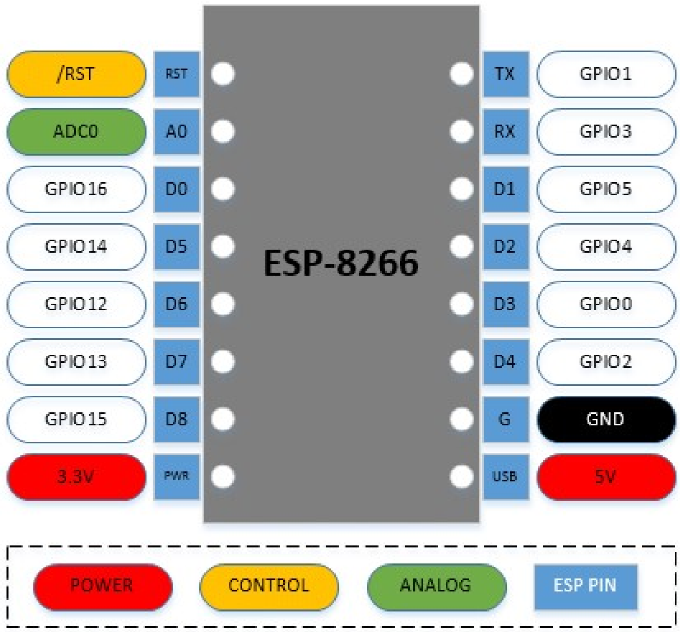


Figure 3.11 Pinout diagram of ESP 8266 Wi-Fi Module [70].

3.4.5 Stimulus Generator

The system incorporates an advanced integrated stimulus generator with unique capabilities designed to address critical limitations of conventional devices. Unlike most commercially available devices that typically employ symmetrical or asymmetrical square pulses using a transformer-MOSFET combination for switching, this generator prioritizes precision and safety in waveform design. Traditional waveforms often fail to achieve complete electrical charge balance, leading to a continuous direct current flow to tissues, which can result in adverse effects over time.

When electrical current passes through an electrode in a conductive solution, chemical reactions occur at the electrode-tissue interface. This highlights the importance of carefully designed waveforms to minimize unintended side effects. Prolonged exposure to high voltage can produce strong faradic currents, resulting in gas formation, electrolysis, and significant pH imbalances. These conditions can accelerate electrode corrosion, compromise device functionality, and potentially damage surrounding tissues.

The generator's design mitigates these risks by ensuring optimal charge balance and reducing the likelihood of adverse reactions. By preventing issues such as electrode degradation and tissue damage, it promotes long-term reliability and patient safety, making it a vital component in advanced biopotential data acquisition systems [14, 71].

To address these concerns, our stimulator employs a biphasic, trapezoidal, charge-balanced pulse with a near-zero DC offset, specifically designed to enhance safety and comfort during stimulation. The use of a trapezoidal waveform is a significant improvement over traditional square pulses, as it ensures gradual transitions in current flow, reducing the likelihood of abrupt stimulation reactions. This smooth modulation minimizes tissue irritation and discomfort, making it ideal for sensitive medical and therapeutic applications.

The charge-balanced nature of the pulse is vital for maintaining electrical neutrality, preventing prolonged direct current exposure that could lead to adverse effects such as tissue damage, electrode corrosion, or pH imbalances at the electrode-tissue interface. By achieving a near-zero DC level, the system ensures long-term patient safety, even during extended stimulation sessions, while preserving electrode integrity and functionality.

Furthermore, the stimulator offers highly customizable parameters to meet diverse application needs. It features an adjustable frequency range from 0 to 45 Hz, allowing precise control over the stimulation rate for various therapeutic and diagnostic purposes. Additionally, the pulse width can be modified between 0 and 350 microseconds, enabling tailored stimulation profiles that accommodate specific patient requirements and treatment goals [72].

3.4.5.1 Design Challenges and Research Gap in Earlier Stimulus Generator Circuit:

While the concept of biphasic waveforms is not entirely new, its practical implementation in biphasic muscle stimulation circuits—particularly with precise control over rise/fall times, charge balancing, and comfort optimization—remains underexplored and technically challenging. For that we have used trapezoidal pulse. My work addresses several engineering, physiological, and safety challenges that earlier researchers either overlooked or could not overcome due to technological limitations.

(i) Reason behind why earlier researchers did not use trapezoidal biphasic pulses:

Generating a true trapezoidal biphasic waveform (with precisely controlled linear rise/fall times and charge balancing between phases) requires more complex analog or mixed-signal circuitry, accurate timing control, and feedback mechanisms to avoid waveform distortion.

Earlier systems often used square/rectangular pulses because they were easier to generate using timers or monostable circuits, especially before the availability of powerful MCUs or DACs.

Power efficiency, size constraints, and component limitations in early bioelectronic systems also made it impractical to implement advanced pulse shaping.

(ii) The challenges in generating this pulse:

Generating a clean trapezoidal waveform—especially in both anodic and cathodic phases—requires:

A digital-to-analog conversion (DAC) or a controlled current/voltage ramp generator.

Precision control of slope (dV/dt or dI/dt), duration, and amplitude to avoid sudden voltage jumps that may defeat the purpose of a trapezoid.

Charge balancing between phases to ensure safety and prevent tissue damage—trapezoids complicate this because energy distribution is not uniform like square waves.

Synchronization with feedback from sensors or electrodes to ensure the waveform does not degrade across the load (i.e., human tissue impedance).

(iii) The novelty in this stimulus generator:

I designed a custom, miniaturized circuit that generates biphasic trapezoidal pulses with tunable rise/fall time, amplitude, and pulse width. This level of programmability and optimization is not found in traditional stimulators.

I demonstrated improved patient/user comfort through reduced sensory discomfort and more natural muscle contraction, which was validated through experimental studies.

I addressed safety by ensuring active charge balancing, zero net DC, and energy-efficient drive circuits, which are critical in wearable/portable applications.

3.4.5.2 Design of the Stimulus Generator:

Figure 3.12 illustrates the block diagram of the stimulus generator. It consists of ESP32 microcontroller, a uniphasic-to-biphasic converter circuit, a current amplifier, a high-voltage operational amplifier, surface electrodes, a boost converter, and a power supply. The ESP32 microcontroller generate two uniphasic pulses that serve as the initial input signals. These pulses are then fed into the uniphasic-to-biphasic converter circuit, which transforms them into a charge-balanced biphasic output. This charge-balanced waveform is crucial for minimizing tissue irritation and ensuring patient safety during stimulation. The amplified biphasic signal is then processed through a current amplifier and a high-voltage operational amplifier to produce the desired stimulation output suitable for therapeutic applications. The stimulation frequency and pulse width are user-adjustable via an external knob. The final output is delivered through surface electrodes, with a skin impedance model integrated into the design to assess and ensure safety before application to the patient.

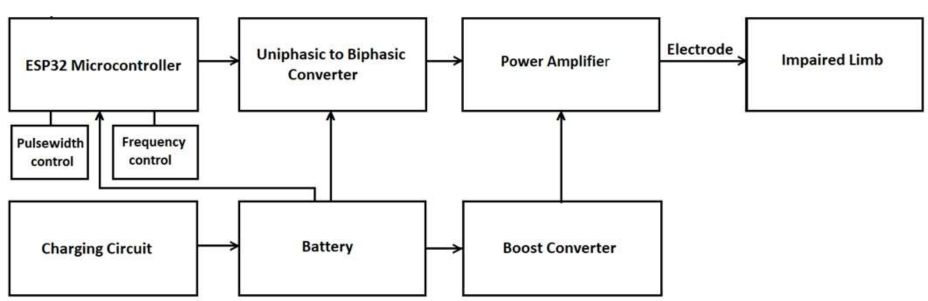


Figure 3.12 Block diagram of stimulus generator.

3.4.5.3 Schematic and Output Waveform Generated by the Stimulus Generator:

Figure 3.13 illustrates the schematic of the stimulator circuit. Two uniphasic pulse trains of trapezoidal shape were generated from pin number 25 and 26 of ESP32, as shown in fig. 3.14. Each pulse on these pulse train has an on-time of T_{on} and off time of T_{off}. There is a phase difference of $\frac{T_{on}}{2}$ between both pulse trains [14]. These uniphasic signals were fed into a uniphasic-to-biphasic converter, which uses an AD620 instrumentation amplifier. Positive pulse for time T_{on} followed immediately by a negative pulse of duration T_{on} followed by 0 V for a time period of T_{off} compose one single pulse. The pulse amplitudes follow a trapezoidal pattern controlled by the ESP32 DAC [14]. This converter produces a charge-balanced biphasic output, which is then applied to an LM324 op-amp. To amplify the current, a Class B amplifier is used to buffer the op-amp output, providing a gain of approximately 13. The BJT ensures high current delivery, with its feedback configuration causing the op-amp to adjust its output in order to match the load voltage to the input voltage. When a positive voltage is applied to the input, the NPN transistor is activated, sourcing current from the NPN transistor to the load. Conversely, when a negative voltage is applied, the PNP transistor is activated, sinking current from the load. Finally, the output from the power amplifier is fed into a high-voltage operational amplifier (PA341DF). The PA341DF is a MOSFET-based operational amplifier that offers high performance and can handle input voltages up to 350 volts, providing an output current of up to 120 mA.

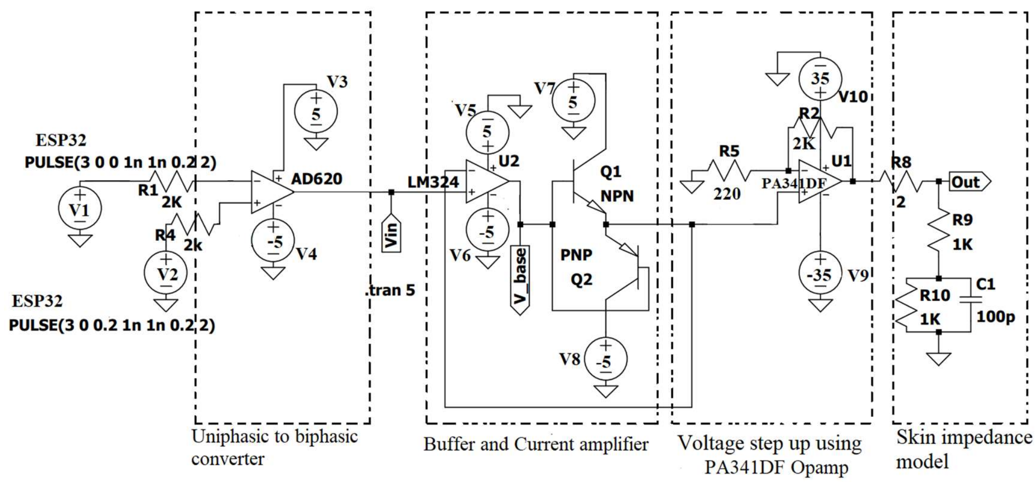


Figure 3.13 Schematic for stimulus generator. The voltages V1 and V2 represent the uniphasic signals generated by the ESP32 microcontroller. These signals are fed into a uniphasic-to-biphasic converter, which incorporates an AD620 instrumentation amplifier. The converter's output is then processed through an LM324 operational amplifier and a Class B amplifier to further refine the signal. The amplified signal is subsequently applied to a PA341DF high-voltage amplifier, which delivers the final output to a skin impedance model, ensuring effective stimulation delivery.

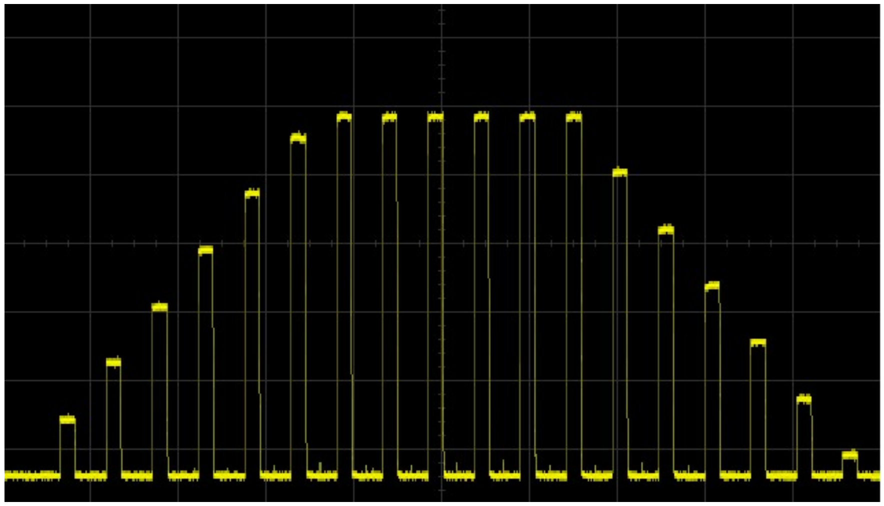


Figure 3.14 Trapezoidal Uniphasic Signal Generated using ESP32 Microcontroller.

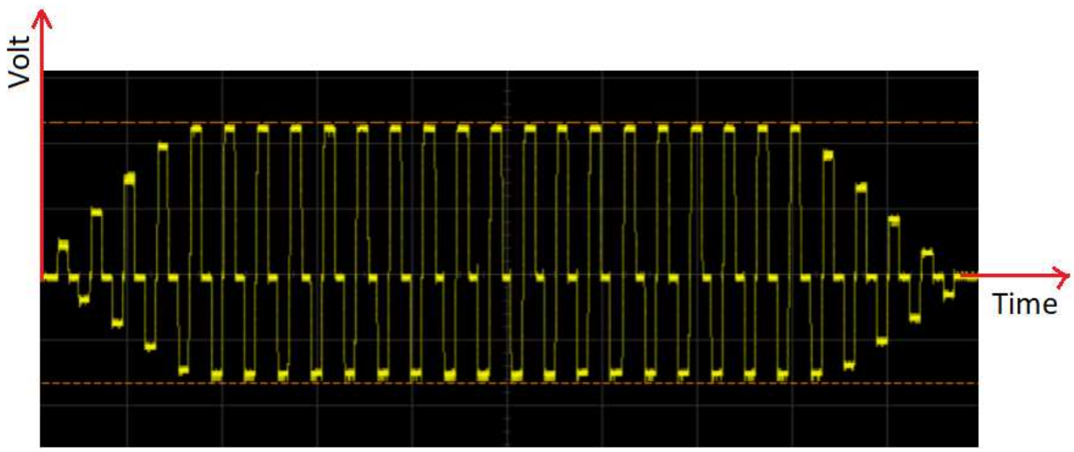


Figure 3.15 Trapezoidal, Biphasic, stimulus viewed in an oscilloscope.

3.4.6 Power Supply Unit

We have used a swappable power supply unit which can be connected externally for easy replacement of battery pack for long term continuous use. When one battery pack got exhausted, another battery pack may be connected externally without disturbing the internal setup. We have used two 3.7V rechargeable Li-ion battery of 2200mAh capacity. The charger circuit was designed using 'TP5100' dual charging module. The 'TP5100' dual charging module offers numerous advantages for charging 7.4V lithium-ion batteries. Its support for dual-cell (7.4V) configurations ensures efficient and reliable charging of high-capacity batteries commonly used in drones, portable devices, and IoT applications. With a high charging current of up to 2A, it enables fast charging, reducing downtime and improving productivity. The module's high efficiency, reaching up to 92%, minimizes energy loss, making it suitable for energy-sensitive applications. Built-in protection features, including overcharge, overcurrent, short-circuit, and reverse polarity safeguards, ensure safe and reliable operation, enhancing battery longevity. The constant current (CC) and constant voltage (CV) charging modes optimize the charging process, preventing battery damage and ensuring stable performance. Additionally, its wide input voltage range (5V to 18V) provides flexibility in power sources, and the compact design allows for easy integration into various devices. With these features, the TP5100 module is a versatile and efficient solution for charging 7.4V lithium-ion batteries. The pinout diagram of the TP5100 charging module is shown in Fig. 3.16.

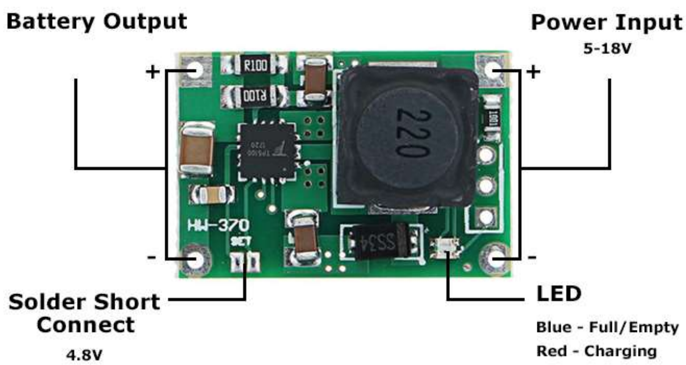


Figure 3.16 Pinout diagram of TP5100 charging module [73].

We have also incorporated a small LCD display with 5 push button switch as a user interface for selecting different biopotential signals like EMG, ECG, EEG and EOG for each channel as input.

3.4.7 Firmware Development

The developed Bio DAQ system operates in a streamlined and efficient manner to ensure accurate signal acquisition and processing. Upon powering up, the device begins by scanning for available Wi-Fi networks. If a network is detected, the system progresses to the next stage, prompting the user to select an input mode. The user assigns a mode to all 16 channels from a predefined list of four signal types: ECG (Electrocardiography), EMG (Electromyography), EEG (Electroencephalography), and EOG (Electrooculography). These selections are stored in the 'ModeList' array, which serves as the configuration reference for the channels. Once the configuration is complete, the system begins acquiring data from each channel using the 'radio.read' function.

The incoming data is then processed based on the signal type specified in the 'ModeList' array. For each channel, the system identifies the corresponding signal type and applies the appropriate filter:

If ModeList[i] == 1, the ECG filter is applied.
If ModeList[i] == 2, the EMG filter is applied.
If ModeList[i] == 3, the EEG filter is applied.
If ModeList[i] == 4, the EOG filter is applied.

The system's signal processing is powered by a set of advanced digital Infinite Impulse Response (IIR) filters, each specifically designed for its respective signal type. These filters are of the fourth order and are tailored to reduce noise and enhance the clarity of the acquired signals. The filtering algorithm is implemented through dedicated functions (e.g., ECGFilter(), EMGFilter()) that process raw data based on the assigned mode for each channel. The raw analog signals from the 16 channels are stored in the 'sensor_value' array, and the filtered outputs are subsequently saved in the 'outPut1' array.

To streamline data handling, the filtered data for all 16 channels are consolidated into a formatted string, 'FouT', which can be used for further analysis or transmission. By combining robust hardware capabilities with sophisticated digital filtering techniques, the Bio DAQ system ensures minimal noise and distortion, significantly enhancing signal fidelity and quality. The firmware's operational flowchart, as depicted in Fig. 3.17, reflects this systematic approach to signal acquisition, filtering, and output generation, making it a highly efficient tool for biopotential data monitoring and analysis.

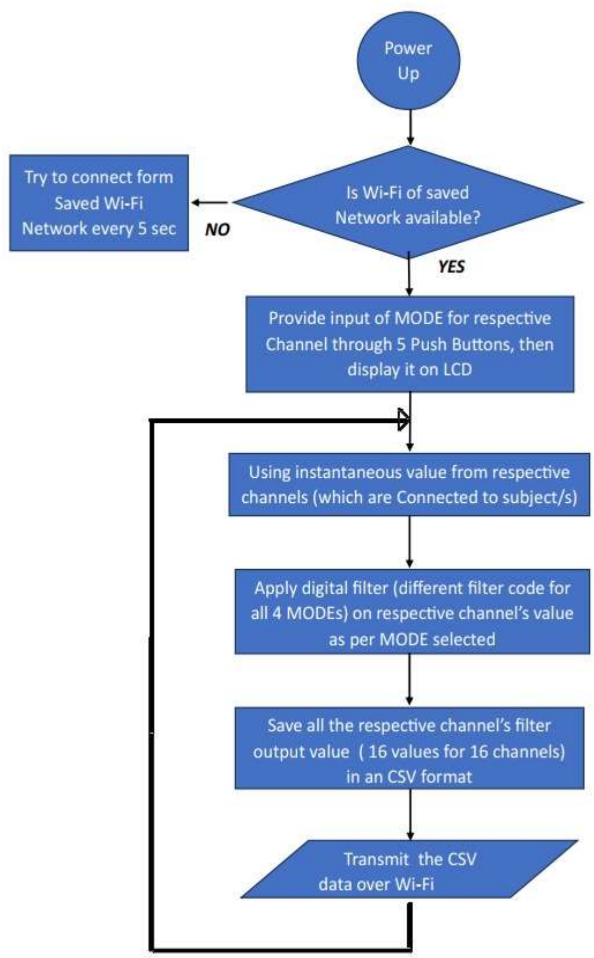


Figure 3.17 Flowchart.

After development of all the subsystems like Analog front end (AFE), Wireless module, Microcontroller Unit (MCU), Stimulator module, Power supply and Display, they were integrated and tested for development of the prototype. The testing and prototype development were described in chapter-4.

CHAPTER - 4

Prototype Development, Testing and Results

Chapter 4

Prototype Development, Testing and Results

4.1. Introduction

The development of a wireless Bio DAQ system represents a significant step toward advancing healthcare monitoring and diagnostics. The integration of different sub systems like modern microcontrollers, low-power wireless communication modules, and efficient signal amplification techniques ensures compactness, portability, and long battery life. Such a system provides real-time data transmission to mobile devices or cloud platforms, facilitating continuous monitoring and remote analysis. The prototype development of this wireless system focuses on achieving reliable signal acquisition, robust wireless transmission, and user-friendly functionality, aiming to enhance accessibility to bio-signal monitoring across clinical, home-based, and research applications.

In this chapter, we delve into the comprehensive process of developing a fully functional prototype by integrating various subsystems, including the Analog Front End (AFE), Microcontroller Unit (MCU), Stimulator Module, Wireless Module, Power Supply, and Display Unit. The chapter outlines the step-by-step journey, starting with the initial circuit implementation on a breadboard, progressing through various stages of testing, and culminating in the creation of a single, cohesive PCB module. Each subsystem is meticulously described, emphasizing its role and contribution to the overall design.

The chapter begins with the breadboard phase, detailing the implementation and iterative testing performed to verify individual subsystems' functionality. This phase ensures that each module operates correctly and interfaces seamlessly with others before moving to the PCB design stage. Various test results obtained during this phase are also discussed, providing valuable insights into the early-stage challenges and their resolutions.

Following the breadboard testing, the integration of all subsystems into a single PCB module is presented. This section describes the PCB design, layout optimization, and the methods used to ensure signal integrity, minimize noise, and achieve compactness. Emphasis is placed on ensuring reliable communication between modules and efficient power distribution across the system.

Finally, the chapter discusses the testing and validation process conducted on the prototype to ensure its safety, performance, and compliance with international standards. Key tests include the Electrical Safety Test as per IEC 60601-1 standard, which evaluates the device's safety when operating in medical environments, and the Electromagnetic Interference (EMI) Test as per CISPR 11 standard, which assesses the system's compliance with electromagnetic compatibility standards. Additionally, the chapter showcases the acquisition of biopotential signals from real-life patients, demonstrating the system's practical application and reliability in capturing high-quality biopotential signals. The test results are analyzed to validate the design and highlight the prototype's effectiveness in meeting its intended objectives.

4.2. Implementation of the Circuit in Breadboard

After development of various subsystems like Analog Front End (AFE), Wireless Module, Microcontroller Unit (MCU), Receiver module; the circuit was initially assembled in breadboard as shown in Fig. 4.1.

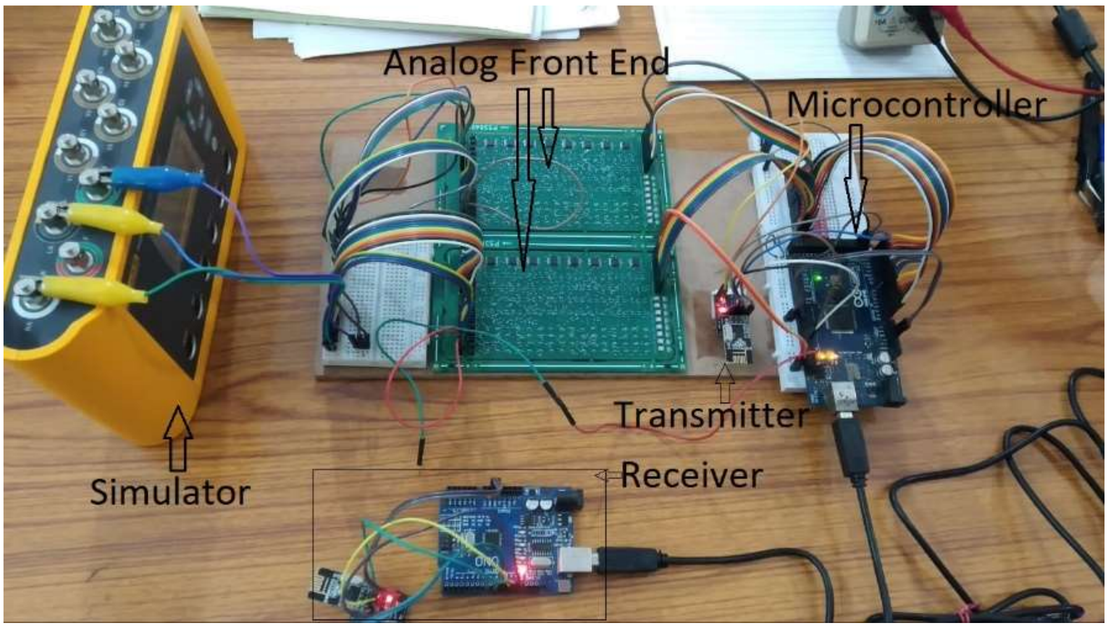


Figure 4.1 Implementation of the circuit in breadboard

The system consists of the following subsystems/components:

(i) ***Analog Front End (AFE) PCB:*** It consists of instrumentation amplifier (IA), low pass filter (LPF), configurable band pass filter (BPF), right leg drive (DRL) circuit, power supply filter and electrode reference selection circuit. Initially we have made two nos 8-channel AFE PCB as shown in Fig 4.1. The 3D design of the 8-channel AFE PCB is shown in Fig 4.2.

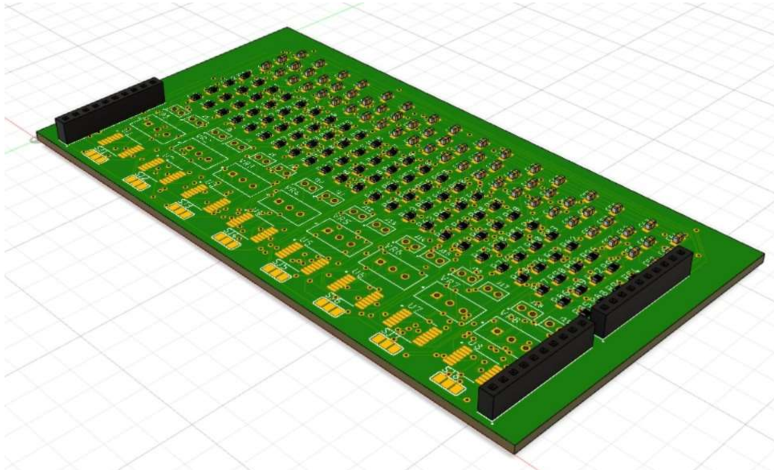


Figure 4.2 3D Design of 8-channel AFE PCB. We have used two 8-channel AFE PCB for using as 16-channel AFE.

(ii) ***Microcontroller Unit (MCU):*** We utilized the ATmega2560 microcontroller through the Arduino MEGA development board, which provides 16 analog input channels, perfectly aligning with our system's requirements. The ATmega2560 offers 256KB of flash memory, ensuring ample storage for firmware, facilitating efficient data acquisition and processing. This microcontroller was chosen for its versatility, robustness, and compatibility with a wide range of sensors and communication interfaces.

The 16 analog signals obtained from the Analog Front End (AFE) are routed to the microcontroller's 16 analog inputs via a DIP switch. This switch allows selective activation of specific channels while grounding unused channels, preventing them from being left in a floating state. This approach effectively mitigates noise interference and enhances the accuracy and reliability of biosignal acquisition.

Once the biosignal data is acquired, the microcontroller reads the data from the measurement block using the SPI (Serial Peripheral Interface). Subsequently, the processed data is transmitted to the wireless module through UART (Universal Asynchronous Receiver-Transmitter), ensuring seamless and efficient data communication for real-time monitoring and analysis.

(iii) ***Wireless Transmitter and Receiver (TRx):*** Initially, we employed the M177 NRF24L01 2.4GHz Wireless Transceiver Module as both the transmitter and receiver due to its effective transmission range of approximately 40-60 meters and low power consumption. This range was a crucial factor in selecting the module, ensuring stable and reliable communication for biosignal data transmission. The NRF24L01 utilizes Gaussian Frequency Shift Keying (GFSK) modulation, which enhances signal integrity by reducing interference and noise in the 2.4 GHz ISM band.

To facilitate data reception and display on a computer, the NRF24L01 module was integrated with an ATmega328 microcontroller via an Arduino Uno development board. The received biosignal data was then transmitted to a computer through the SPI (Serial Peripheral Interface), enabling real-time monitoring and analysis.

One of the major limitations of NRF24L01 module is that it requires external components like microcontrollers to handle protocols and manage data processing. This system cannot be integrated to any computer or network without having any receiver module. Due to this, later we have changed our design and chosen ESP 8266 Wi-Fi module for our wireless transmitter design as it does not require any external hardware like microcontroller at the receiver end.

(iv) ***Stimulus Generator:*** Stimulus generator circuit consists of ESP32 microcontroller, a uniphasic-to-biphasic converter circuit, a current amplifier, a high-voltage operational amplifier, surface electrodes and a boost converter. This circuit was also initially implemented in breadboard and tested as shown in Fig 4.3.

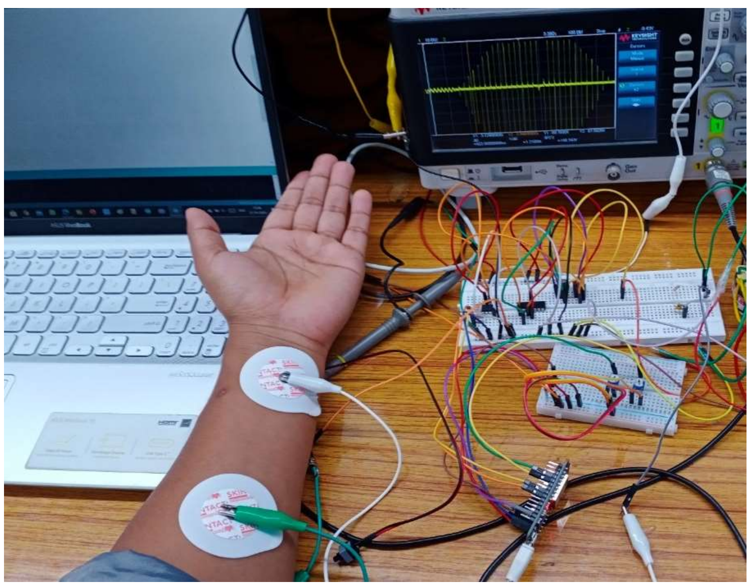


Figure 4.3 Implementation of the stimulator circuit in the breadboard. The output of the circuit was applied to hand using the surface electrode.

(v) ***Simulator:*** We used Fluke ProSim 2 Vital Signs Simulator for using as a human interface or patient. It is a compact and versatile device designed for testing and calibrating patient monitoring systems. It provides precise simulation of vital signs, including ECG, blood pressure, temperature, and SpO_2, ensuring the accuracy and reliability of medical equipment. With its user-friendly interface and battery-powered operation, the ProSim 2 is highly portable, making it ideal for laboratory testing. The simulator features configurable waveforms and test parameters, allowing researchers to perform comprehensive evaluations of Bio DAQ systems in compliance with industry standards.

Its high-fidelity signal generation ensures accurate performance verification, reducing the risk of equipment failure in clinical settings. Designed for efficiency, the Fluke ProSim 2 enhances troubleshooting and maintenance workflows, ensuring that medical devices deliver precise and reliable patient readings in critical healthcare environments.

4.3. Testing of the Circuit in Breadboard

After implementing the circuit in breadboard, various tests were conducted to evaluate the ability of signal acquisition. We used Fluke ProSim 2 Vital Signs Simulator for using as a human interface or patient for performing the tests. The tests conducted as follows:

4.3.1. Test with Normal ECG Signals

ECG signals were obtained using the Fluke ProSim 2 ECG Simulator, configured with a sampling rate of 125 Hz to ensure accurate signal representation. Data acquisition was performed at a baud rate of 115200, facilitating efficient communication between the system and the processing unit. The developed system was initially tested using standard ECG waveforms to verify its capability to capture and process physiological signals reliably. The simulator was connected to the system as illustrated in Fig.4.1, ensuring proper electrode placement and signal integrity. This setup allowed for the validation of the system's performance under controlled conditions before real-world application. Arduino IDE software was used for viewing the signals. The developed Bio DAQ system successfully acquired normal ECG signals which was shown in Fig.4.4.

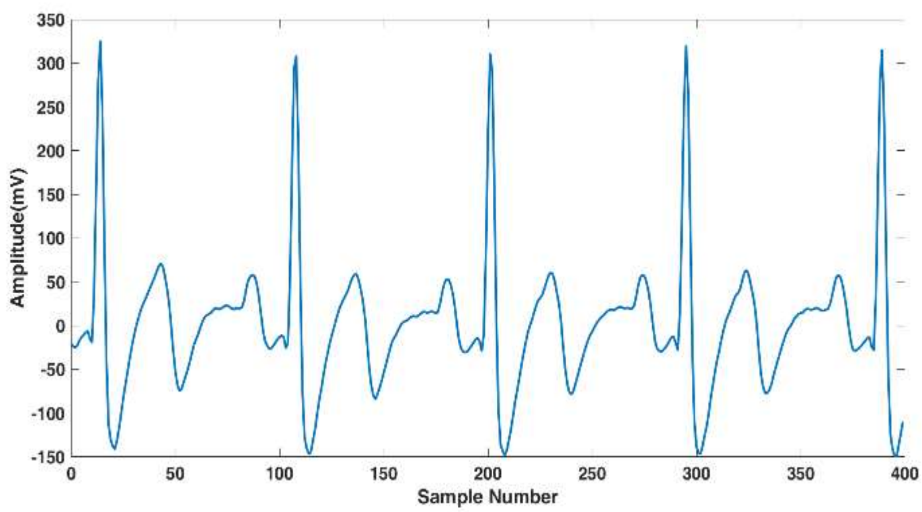


Figure 4.4 Normal ECG waveform acquired by the Bio DAQ system.

4.3.2. Test with Critical ECG Signals and Arrhythmias

Arrhythmia refers to an irregular heart functions caused by disruptions in the electrical impulses that regulate heart rhythm. It can manifest as tachycardia (fast heart rate), bradycardia (slow heart rate), or irregular patterns such as atrial fibrillation, flutter, heart block etc. Arrhythmias can be benign or life-threatening, depending on their type and severity. Common causes include electrolyte imbalances, heart disease, high blood pressure, stress, excessive caffeine intake, or genetic predisposition. Diagnosis is typically performed using electrocardiography (ECG), or wearable biosignal acquisition systems. Continuous monitoring of arrhythmias using advanced biosignal acquisition devices is crucial for effective management and early intervention.

After successfully acquiring normal ECG signals, the developed Bio DAQ system was further evaluated for its ability to acquire various critical ECG abnormalities and arrhythmias commonly observed in the human body. To conduct this assessment, we utilized the Fluke ProSim2 Simulator, a highly reliable biomedical test device capable of generating a wide range of pathological ECG waveforms that closely mimic real human physiological conditions. The simulator was programmed to produce different arrhythmic patterns, including first degree heart block, second degree heart block, atrial fibrillation, atrial flutter, among others. By analyzing the system's response to these simulated arrhythmic signals, we were able to validate its accuracy, sensitivity, and reliability in detecting critical ECG abnormalities, ensuring its effectiveness for real-world medical applications.

(i) ***Acquisition of Atrial Fibrillation Signal:*** Atrial fibrillation (AF) is a common cardiac arrhythmia characterized by irregular and rapid electrical activity in the atria, leading to the loss of coordinated atrial contractions. In an ECG waveform, AF is identified by the absence of distinct P waves and the presence of irregularly spaced R-R intervals due to chaotic atrial impulses. Instead of P waves, fibrillatory (f) waves appear as rapid, erratic oscillations, typically between 350-600 bpm. These irregular atrial activations result in an unpredictable ventricular response, making AF detection crucial for clinical diagnosis and management. We have used the Fluke ProSim2 Simulator for generating atrial fibrillation waves similar to generated by the human body. The Bio DAQ system was able to successfully acquire atrial fibrillation signals which was shown in Fig.4.5.

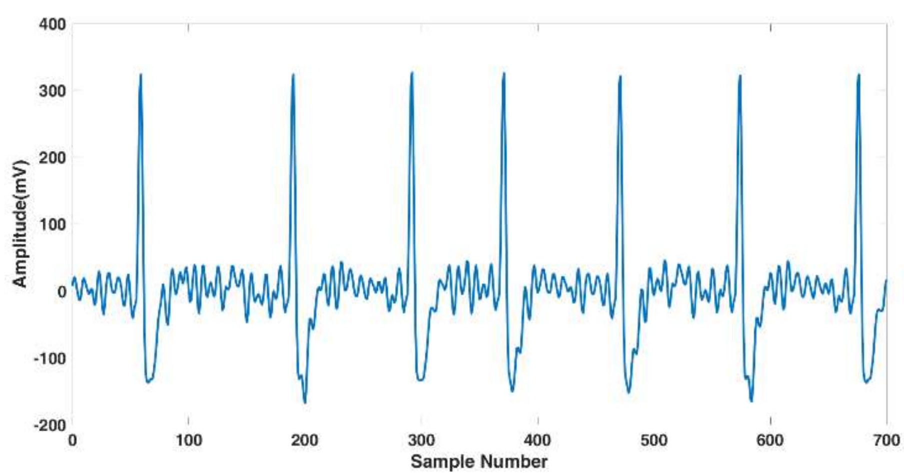


Figure 4.5 Atrial fibrillation waveform acquired by the Bio DAQ system.

(ii) ***Acquisition of First-Degree Heart Block Signal:*** First-degree heart block is a mild conduction abnormality where electrical impulses from the atria to the ventricles are delayed but not blocked. In an ECG waveform, it is characterized by a prolonged PR interval greater than 200 milliseconds (0.20 seconds) while maintaining a consistent P wave before each QRS complex. Unlike higher-degree heart blocks, first-degree heart block does not cause dropped beats, and the ventricular rhythm remains regular. Though often asymptomatic, it can indicate underlying conduction system disease or be a side effect of medications affecting AV node conduction. We have used the Fluke ProSim2 Simulator for generating atrial fibrillation waves similar to generated by the human body and the Bio DAQ system was able to successfully acquire first degree heart block signals which was shown in Fig.4.6.

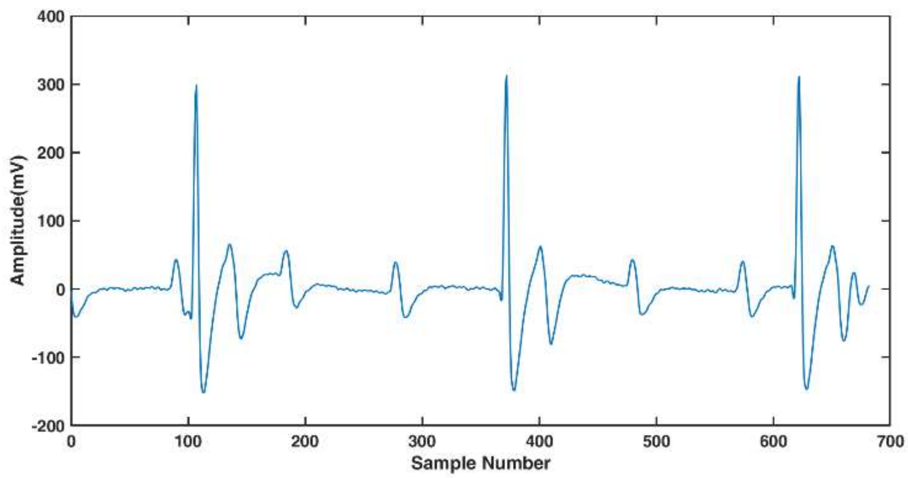


Figure 4.6 First degree heart block waveform acquired by the Bio DAQ system.

(iii) ***Acquisition of Second Degree Heart Block Signal:*** Second-degree heart block is a conduction abnormality where some electrical impulses from the atria fail to reach the ventricles, leading to intermittent dropped beats. It is classified into Mobitz Type I (Wenckebach) and Mobitz Type II. The PR interval progressively lengthens with each beat until a QRS complex is dropped. This pattern then repeats, resulting in an irregular rhythm. Sometimes, the PR interval remains constant, but intermittent QRS complexes are absent, leading to sudden dropped beats without prior warning. This type is more serious and may progress to complete heart block. Second-degree heart block can cause dizziness or syncope, which often requires pacemaker intervention. We utilized the Fluke ProSim2 Simulator for generating atrial fibrillation waves similar to generated by the human body, and the Bio DAQ system successfully captured second degree heart block signals, as illustrated in Fig. 4.7.

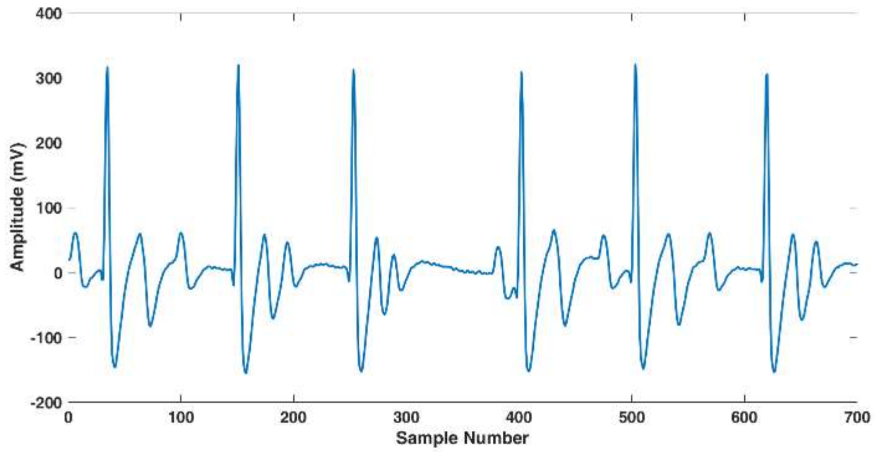


Figure 4.7 Second degree heart block waveform acquired by the Bio DAQ system.

(iv) ***Acquisition of Atrial Flutter Signal:*** Atrial flutter is an abnormal heart rhythm characterized by rapid, repetitive electrical signals in the atria. This pattern appears as a series of flutter waves, typically at a rate of around 250-350 beats per minute, which is much faster than normal atrial contractions. On the ECG, these flutter waves are most prominent in the II, III, and aVF leads, and there is often a 1:2 or 1:3 conduction ratio to the ventricles, meaning not every atrial impulse is passed to the ventricles. This results in a regular ventricular rhythm but with an abnormal atrial response. Atrial flutter can lead to poor heart efficiency and increases the risk of blood clots and stroke, making it important to monitor and treat accordingly. We used the Fluke ProSim2 Simulator, and the Bio DAQ system effectively recorded signals of atrial flutter, as shown in Fig. 4.8.

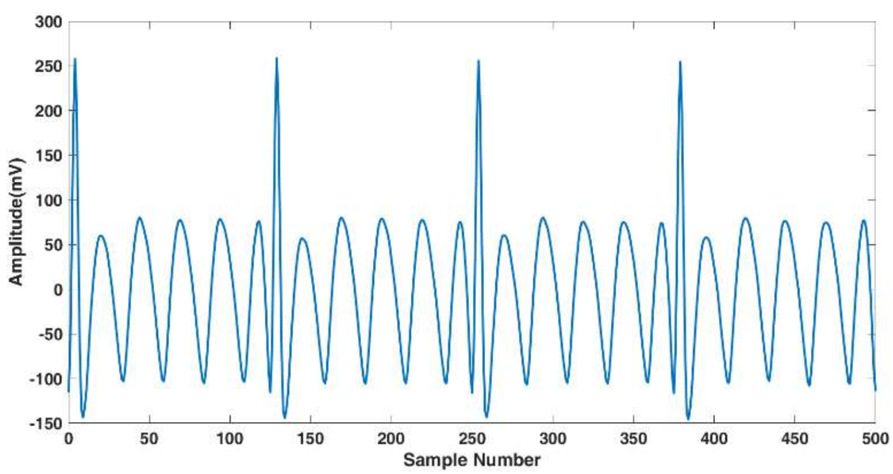


Figure 4.8 Atrial flutter waveform acquired by the Bio DAQ system.

4.4. Development of Prototype

After successfully acquiring various biopotential signals and conducting extensive testing on different parameters, the prototype PCB was meticulously designed and developed to integrate all essential subsystems into a single, compact, and portable unit. This PCB incorporates critical components such as the Analog Front End (AFE), Wireless Module, Microcontroller Unit (MCU), and Display, along with push-button switches, ensuring smooth functionality and efficient operation. The 3D design of the PCB, as illustrated in Fig. 4.9, was carefully optimized to achieve a final size of 19 cm × 10 cm, making it both space-efficient and user-friendly. By focusing on an integrated and compact design, the system enhances usability while maintaining high signal accuracy and reliability.

One of the key innovations in our design is the use of vertical interconnecting connectors to integrate all subsystems, completely eliminating the need for external wiring. This not only simplifies assembly but also significantly reduces noise interference, a crucial aspect that was validated during Electromagnetic Interference (EMI) testing. The reduction in EMI ensures higher signal integrity and improved overall system performance. The final fabricated and fully assembled PCB, shown in Fig. 4.10, successfully meets the expected design criteria in terms of efficiency, portability, and durability. Additionally, a comprehensive list of all components used in the PCB, including their specifications, is provided in Appendix as the Bill of Materials (BOM) for further reference.

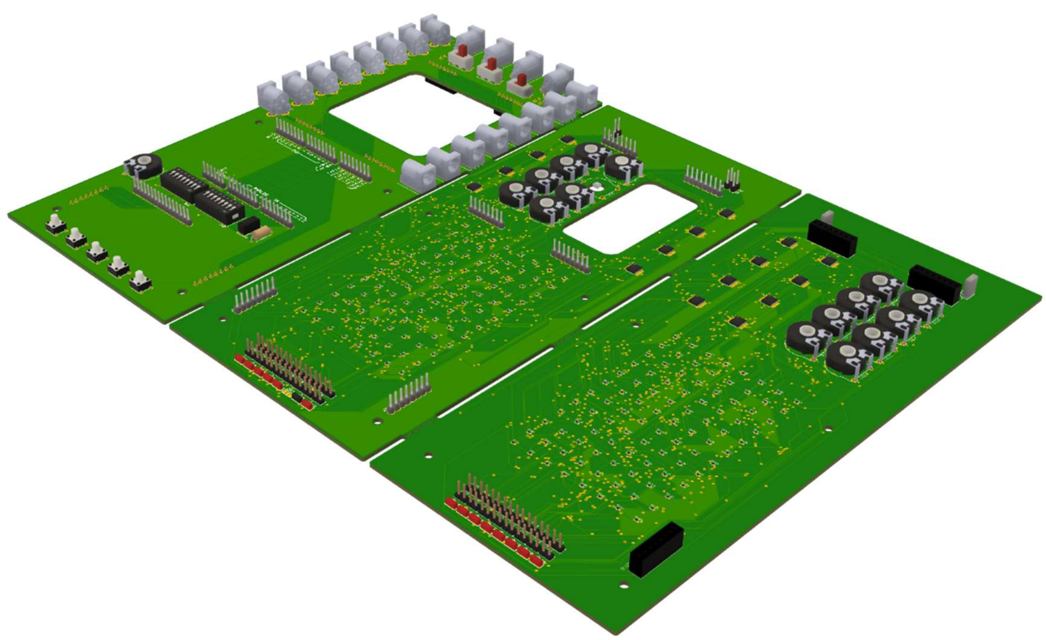


Figure 4.9 3D Design of the Prototype PCB.

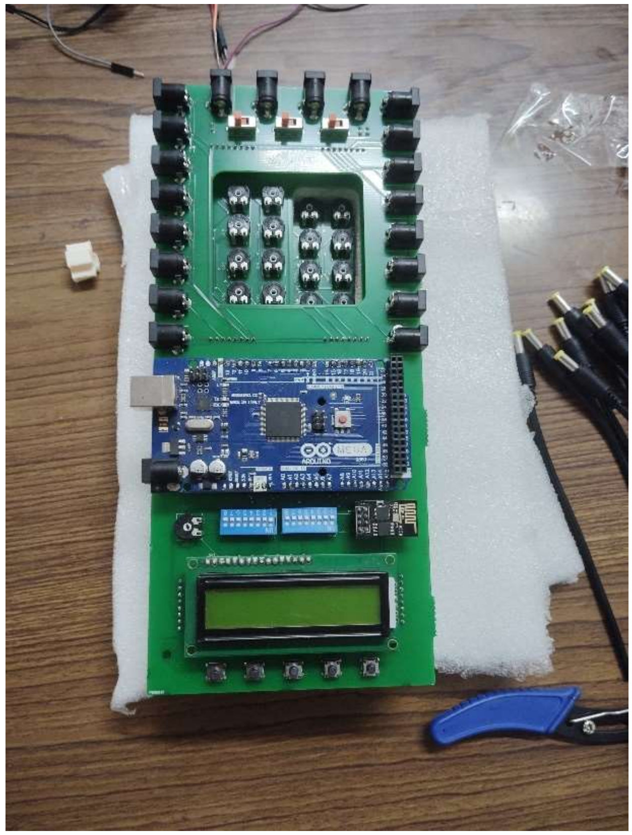


Figure 4.10 Fabricated and fully assembled Prototype PCB.

After fabricating the prototype PCB, an external casing was designed and manufactured using a 3D printer to provide structural integrity and protection to the internal components. The casing was carefully designed to accommodate all essential modules while ensuring ease of access for maintenance and upgrades. A swappable power supply module was integrated into the enclosure, allowing flexibility in power management. The power module features an on-off switch for convenient operation and an LED indicator to provide real-time status updates, ensuring users are informed about the system's operational state. Additionally, the stimulator unit was securely incorporated within the casing, making the final prototype a compact, portable, and user-friendly device. The fully assembled prototype, with all integrated components, is shown in Fig. 4.11.

Figure 4.11 Final Prototype.

4.5. Results

This prototype serves as a versatile platform for a wide range of biomedical applications, expanding its usability beyond simple bio potential signal acquisition. It can be utilized in clinical trials for monitoring physiological data, aiding in rehabilitation research, and enhancing prosthetic device development. Additionally, the system provides a foundation for studying various types of stimulators and their effects on muscles and nerves, facilitating advancements in neuromuscular therapy.

To ensure the safety, reliability, and effectiveness of our design, the prototype underwent rigorous testing in accordance with international standards. These tests included: (1) Electrical safety testing as per IEC 60601-1 standard, ensuring compliance with medical device safety regulations; (2) Electromagnetic Interference (EMI) testing according to CISPR 11 standard, verifying that the device operates without causing or experiencing electromagnetic disturbances; (3) Wireless transmission range test; (4) Functional validation test through simulated and real-life biosignal acquisition, capturing critical physiological signals such as EMG, ECG, EOG, and EEG from human subjects; (5) Stimulator pulse characteristics test based on pulse width; (6) Stimulator pulse characteristics test based on frequency; (7) Reconfigurability test to validate the compatibility of our system with both 2-electrode and 3-electrode configurations; (8) Power consumption and Noise amplitude measurement.

By successfully passing these tests, the prototype demonstrates its potential as a reliable and robust tool for medical and research applications, paving the way for future enhancements and integration into real-world healthcare settings.

4.5.1. Wireless Transmission Range Test

The Bio DAQ prototype was initially evaluated for its transmission range by testing simultaneous signal acquisition across all 16 channels at distances ranging from 10 to 60 meters. The system demonstrated reliable performance, successfully transmitting signals without noticeable distortion up to 40 meters. Beyond this range, signal quality began to degrade, indicating that 40 meters is the optimal operating distance for maintaining accurate and distortion-free data acquisition.

However, beyond 40 meters, a gradual decrease in signal speed was observed, along with increasing distortion that impacted the accuracy of the transmitted data. This limitation can be attributed to the inherent characteristics of the wireless transmission module and external environmental factors, such as interference and signal attenuation, which affect overall transmission stability.

Despite this limitation, the prototype achieved a reliable transmission range of 40 meters, outperforming many existing systems, as shown in Table 2.1. This performance underscores the efficiency and robustness of the developed system, achieved our intended objective of achieving at least 30m wireless transmission range and thereby positioning it as a competitive and effective solution for wireless Bio DAQ applications.

4.5.2. Electrical Safety Test as per IEC 60601-1 Standard

The IEC 60601-1 standard, established by the International Electrotechnical Commission (IEC), serves as a globally recognized benchmark for the safety, reliability, and essential performance of medical electrical equipment. Adhering to this standard is vital for minimizing risks to patients, healthcare providers, and the surrounding environment while ensuring that medical devices operate safely and effectively under diverse conditions. Complying with IEC 60601-1 is a key requirement for regulatory approvals in many countries, making it an essential aspect of medical device development.

Electrical safety testing, as required by IEC 60601-1, encompasses several critical assessments, including chassis leakage current, patient lead leakage current, earth leakage, and insulation resistance tests. These evaluations are essential to ensure that the device does not present any electrical hazards during operation. To perform these tests on our prototype, we employed the Fluke ESA612 Electrical Safety Analyzer, a widely recognized instrument for comprehensive medical device safety assessments. A photograph of the prototype undergoing testing with the Fluke ESA612 Electrical Safety Analyzer is presented in Fig. 4.12.

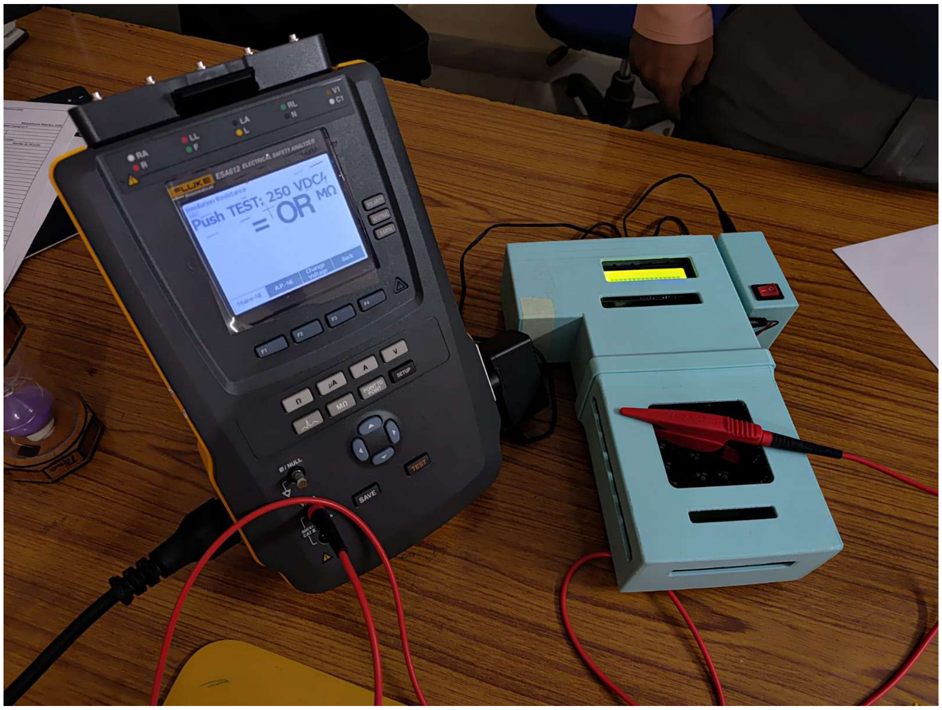


Figure 4.12 Electrical safety test on the Prototype.

Among the tests performed, the insulation resistance test involved injecting 250V DC into the prototype's enclosure to evaluate its insulation integrity. All tests were conducted under normal conditions (NC) to simulate real-world operational scenarios. Our developed system uses surface electrode to the patient body, hence it comes under type BF (body float) is where electrical contact is made. The results obtained from these evaluations, along with the permitted limits defined by the IEC 60601-1 standard, are presented in Table 4.1, confirming the prototype's compliance with international safety standards.

Table 4.1 Electrical Safety Test Results of the Prototype

Parameter	**Permitted values**	**Measured Values**	**Deviation**	**Pass/Fail**
Chassis Leakage Current	<100µA	1 µA	Nil	Pass
Patient Leakage Current	<100µA for BF	0.4 µA	Nil	Pass
Earth Leakage Current	<5mA	0.6 µA	Nil	Pass
Insulation Test	<2MΩ	>20 MΩ	Nil	Pass

The extremely low chassis leakage current indicates excellent insulation and grounding, ensuring patient safety and preventing unintended electrical shocks. The negligible patient leakage current confirms minimal risk of electrical exposure to the patient. The extremely low earth leakage current demonstrates proper grounding and electrical isolation, reducing the risk of electric shock hazards. The insulation resistance is far beyond the required threshold, indicating strong dielectric protection and high insulation integrity of the device.

The test results revealed that the measured values for various safety parameters of our prototype were significantly lower than the permissible limits specified in the IEC 60601-1 standard. This indicates that the device operates well within the safety thresholds, ensuring minimal risk to users and patients.

By successfully passing all required safety tests, including leakage current, earth leakage, and insulation resistance assessments, our prototype meets the stringent safety criteria established for medical electrical equipment. These results confirm that the device is not only compliant with international safety regulations but also reliable for real-world biomedical applications. The successful validation of our design through rigorous testing underscores its safety, reliability, and effectiveness in medical and research environments.

4.5.3. Electromagnetic Interference (EMI) Test as per CISPR 11 Standard

The Electromagnetic Interference (EMI) test is a critical assessment conducted on all medical equipment before commercialization to ensure patient safety, device reliability, and regulatory compliance with standards such as European CE and US FDA regulations. This test ensures that the device does not emit excessive electromagnetic interference that could affect its functionality or disrupt surrounding medical equipment.

To evaluate EMI performance, we conducted a radiated emission test on our prototype following the CISPR 11 standard, a globally recognized Electromagnetic Compatibility (EMC) standard applicable to industrial, scientific, and medical (ISM) equipment operating up to 400 GHz. The test was carried out in a 3-meter semi-anechoic chamber, where the prototype, referred to as the Equipment under Test (EUT), was placed on a 1m x 1.5m non-conductive table, 0.8m above the ground plane and centered on the turntable rotating table. This setup allowed us to capture emissions at all angles, ensuring a comprehensive assessment of radiated emissions.

For measurements ranging from 30 MHz to 6 GHz, a Biconical Antenna was connected to a Spectrum Analyzer. The pre-scanning process involved measuring peak emissions across a full 360-degree rotation at varying antenna heights (ranging from 1 m to 4 m) for both horizontal and vertical polarizations. Given that our prototype operates within the 2.4 GHz frequency band, we specifically focused on emissions within the 1–6 GHz range. Testing was conducted for both antenna orientations to ensure compliance across different signal alignments. The schematic of the test setup is illustrated in Fig. 4.13, while Fig. 4.14 presents a photograph of the prototype undergoing testing.

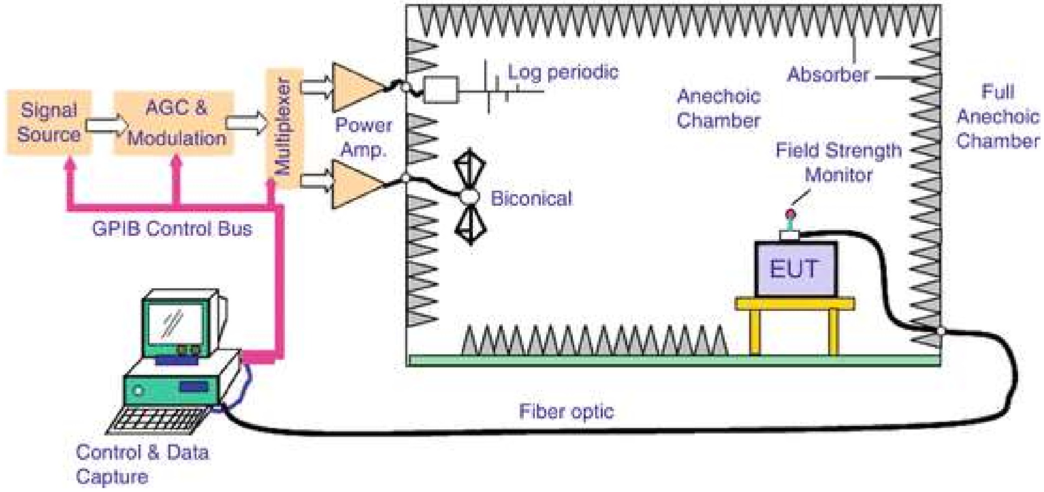


Figure 4.13 Schematic of Test setup for EMI Test [74].

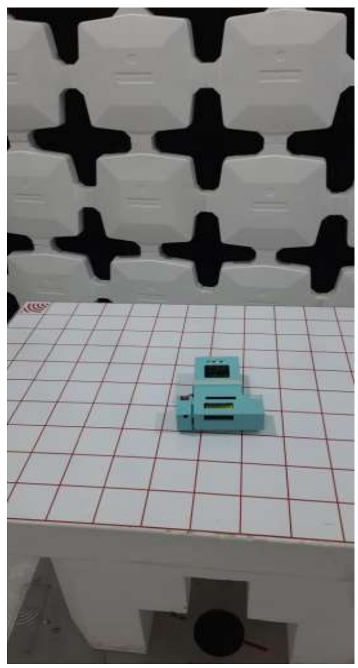
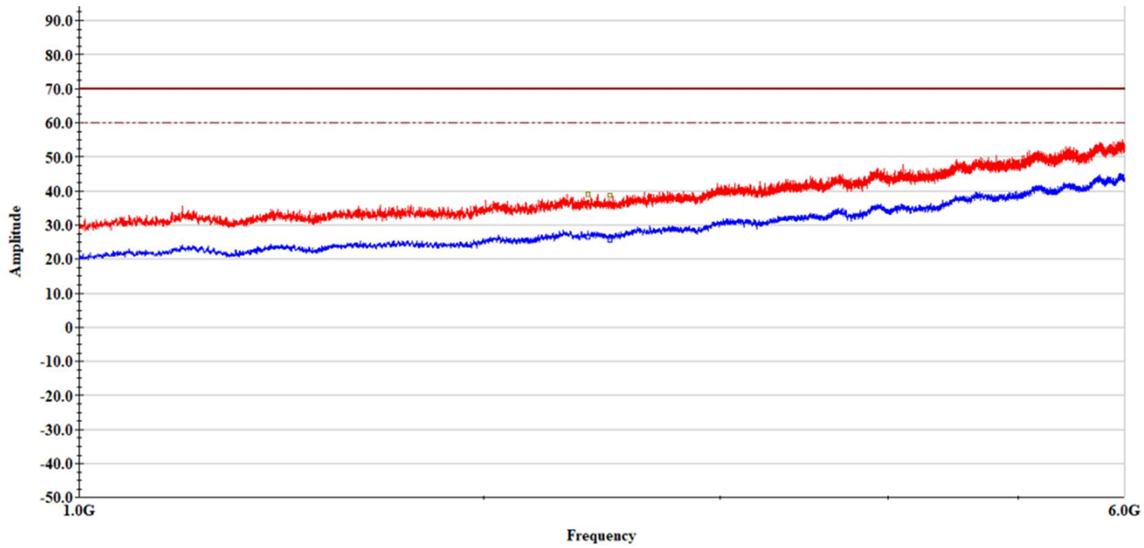
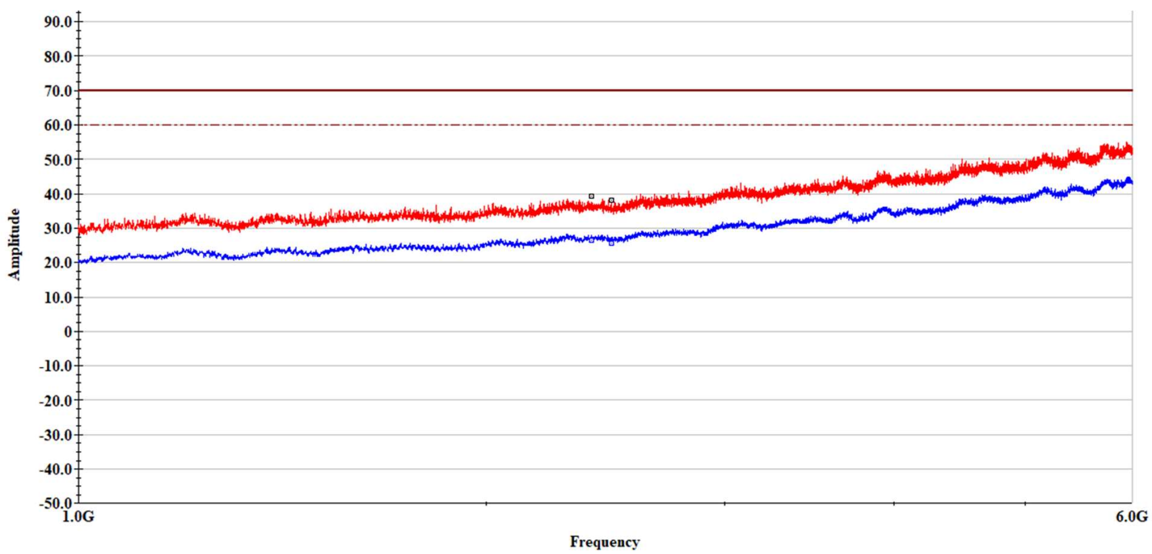


Figure 4.14 EMI Test on the Prototype.

The emissions measured by both horizontal and vertical antenna polarizations are shown in Fig. 4.15(a&b) and the test results are summarized in Table 4.2.



(a) Graph of Emissions received in Horizontal Antenna positions in frequency range of 1-6 GHz



(b) Graph of Emissions received in Vertical Antenna positions in frequency range of 1-6 GHz

Figure 4.15 Emissions measured by both horizontal and vertical antenna polarizations during EMI Test on the prototype

Table 4.2 EMI Test Results of the Prototype

Freq	Measurement Type	Raw Data (dBµV)	Cable Loss (dB)	Antenna Factor (dB/m)	Corrected Data (dBµV/m)	Limit (dBµV/m)
1-6 GHz	Vertical Peak emission	31.639	-22.475	30.028	39.192	70
1-6 GHz	Vertical Average emission	18.800	-22.475	30.028	26.353	60
1-6 GHz	Horizontal Peak emission	31.3786	-22.489	30.0440	38.934	70
1-6 GHz	Horizontal Average emission	18.885	-22.489	30.0440	26.440	60

During the vertical scanning, our prototype exhibited a peak emission of 39.192 dBµV/m, which is well below the permissible limit of 70 dBµV/m, and an average emission of 26.353 dBµV/m, significantly lower than the allowed 60 dBµV/m. Similarly, in the horizontal scanning, we observed a peak emission of 38.934 dBµV/m, again staying well within the 70 dBµV/m limit, and an average emission of 26.440 dBµV/m, which is far below the 60 dBµV/m threshold.

These test results clearly demonstrate that our prototype emits significantly lower electromagnetic interference than the permissible limits specified in the CISPR 11 standard. The compliance of our device with these stringent emission standards not only validates our design methodology but also confirms the careful selection of components, ensuring that our system operates efficiently without causing electromagnetic disturbances in its environment.

4.5.4. Stimulator Pulse Characteristics Test based on Pulse width

The pulse width of a stimulation pulse in a stimulator plays a crucial role in determining the effectiveness and comfort of electrical stimulation. It directly influences the depth of muscle activation, recruitment of nerve fibers, and overall stimulation efficiency. Optimizing pulse width ensures targeted muscle activation while minimizing discomfort, preventing excessive fatigue or potential tissue damage. It also helps accommodate different patient needs, making muscle stimulators more versatile for rehabilitation, therapy, and performance enhancement applications.

The characteristics of the stimulation pulse were analyzed by systematically varying the stimulation pulse width while keeping other parameters constant. Specifically, the stimulation frequency was fixed at 35 Hz, and the stimulation voltage was maintained at 70 volts peak-to-peak to ensure consistency in the study.

This investigation aimed to understand how changes in pulse width affect the overall stimulation response, which is crucial for optimizing the system for different biomedical applications. By fine-tuning the pulse width, the system can be tailored to deliver precise and effective stimulation, minimizing discomfort while maximizing therapeutic benefits.

The detailed characteristics and parameters derived from this study are summarized in Table 4.3, providing a comprehensive overview of how different pulse width settings influence stimulation performance.

Table 4.3 Stimulation Pulse Characteristics based on Pulse width

Sl No.	Pulse-width (µSec)	Characteristics	Total Time (mS)
1	10	No effects	766
2	40	Very small twist (**Sensory Threshold**)	767
3	60	,,	768
4	80	,,	770
5	100	Visible contraction **(Motor Threshold)**	772
6	120	More visible contraction	775
7	140	Smooth (**Operational Intensity**)	780
8	160	,,	785
9	180	,,	790
10	200	,,	795
11	220	,,	800
12	240	Smooth (**Operational Intensity)**	805
13	260	Strong	810
14	280	Strong	812
15	300	Strong	814
16	320	Stronger	824
17	340	Stronger	835
18	360	,,	844
19	380	,,	850
20	400	,,	854
21	420	**Maximum Tolerable Intensity**	866

From Table 4.3, we have found that, as the pulse width increases, the muscle contraction becomes stronger. The pulse width can range from 0 to 350 microseconds, with smooth muscle contractions typically occurring between 140 and 240 microseconds. Similarly, increasing the stimulation frequency also strengthens the muscle contraction. It is essential to recognize that stimulation characteristics can differ among individuals, as each person's physiological response to stimulation is unique.

4.5.5. Stimulator Pulse Characteristics Test based on Frequency

The frequency of a stimulation pulse in a muscle stimulator is essential in controlling the type of muscle response and the therapeutic outcome. Based on the frequencies, muscle produces twitch-like contractions, sustained contractions, and tetanic contractions. By adjusting the frequency, a muscle stimulator can be fine-tuned to target specific muscle fibers, optimize therapeutic outcomes, and enhance both comfort and effectiveness for the user.

The characteristics of the stimulation were analyzed by varying the stimulation frequency while keeping other parameters constant. The pulse width was fixed at 300 microseconds, ensuring consistent nerve activation, and the stimulation voltage was maintained at 70 volts peak-to-peak to deliver a stable and effective stimulus. This approach allowed for a controlled evaluation of frequency-dependent effects on muscle response. Table 4.4 provides a detailed overview of the stimulation characteristics and key parameters used in this study.

Table 4.4 Stimulation Pulse Characteristics based on Frequency

Sl. No.	Pulse period (µSec)	Frequency (oscilloscope)	Pulse Characteristics	Total Time (mSec)
1.	20000	50Hz	Not comfortable	622
2.	21000	47Hz	Not comfortable	624
3.	22000	45 Hz	More stronger	646
4.	23000	43 Hz	Stronger	668
5.	24000	41.13 Hz	Stronger	678
6.	26000	38 Hz	Stronger	701
7.	28000	35 Hz	Smooth	787
8.	29000	34.1 ,,	,,	798
9.	30000	33.33 ,,	,,	801
10.	31000	32.25 ,,	,,	842
11.	33000	30.3 ,,	,,	902
12.	34000	29.4 ,,	,,	954
13.	40000	25 Hz	,,	1.1 sec
14.	45000	22 Hz	Slow contraction	1.2 sec
15.	50000	20 Hz	Slow ,,	1.4 sec
16.	55000	18.1 Hz	Slow twist	1.5 sec
17.	60000	16.66 Hz	,,	1.69 ,,
18.	65000	15.3 Hz	Very small twist	1.79 ,,
19.	70000	14.2 Hz	,,	1.88 ,,
20.	80000	12.5 Hz	,,	1.98 ,,

The stimulation frequency in the system can be adjusted within a range of 0 Hz to 45 Hz, allowing flexibility in muscle activation. It was observed from Table 4.4 that muscle contractions remain smooth and controlled between 25 Hz and 35 Hz, making this range optimal for comfortable and effective stimulation. Although the maximum tested frequency was 50 Hz, it resulted in stronger muscle contractions but was found to be less comfortable for the patient.

To further analyze the effects of stimulation, both pulse width and frequency were varied. Higher frequencies tend to increase muscle contraction strength, but they also accelerate muscle fatigue, which may limit prolonged use. Additionally, stimulation characteristics can vary from person to person, as individual physiological differences influence how muscles respond to electrical impulses. Therefore, personalized adjustments are essential to ensure optimal comfort and efficiency in muscle stimulation therapy.

4.5.6. Functional Test with Real life signals

After successfully completing various safety tests and simulator-based evaluations, we conducted limited testing on human subjects to assess the prototype's capability in acquiring real-life biopotential signals, including ECG (Electrocardiogram), EMG (Electromyogram), EOG

(Electrooculogram), and EEG (Electroencephalogram).

These real-world tests were essential to validate the system's performance, signal fidelity, and robustness in practical conditions. The prototype was connected to human subjects following standard electrode placement techniques to ensure accurate signal acquisition while minimizing noise and interference. The results were analyzed to confirm that the acquired signals maintained clarity, stability, and consistency with expected physiological waveforms.

Ag/AgCl (Silver/Silver Chloride) surface electrodes are widely preferred for acquiring biopotential signals due to their high conductivity, stability, and low impedance. They provide excellent signal quality with minimal noise and artifact interference, ensuring accurate and reliable measurements of biopotential signals such as ECG, EEG, and EMG. The biocompatibility of Ag/AgCl electrodes makes them safe for prolonged contact with the skin, reducing the risk of irritation. Additionally, their ability to maintain a stable half-cell potential enhances signal consistency, making them ideal for both clinical and research applications in Bio DAQ systems. Due to these advantages, we used Ag/Agcl surface electrodes for acquiring all the biopotential signals.

This real-life validation demonstrated the prototype's effectiveness in capturing biopotential signals and its potential applicability in clinical and research settings for continuous monitoring and biomedical analysis.

4.5.6.1 Statistical Requirements and Biopotential Signal acquisition Rigor

The test was carried out very limitedly to validate the system's performance in real world environment. The statistical requirements and signal acquisition rigor is mentioned below.

a. Sample Size: One healthy volunteer for each type of signal.
b. Power Analysis: Design for 80% power at $\alpha = 0.05$ to detect a 5% change in signal amplitude.
c. Signal Quality Metrics:
   Peak to peak noise amplitude of typically < 2 μW for reliable analysis.
   Crosstalk/Artifact Rejection Ratio- Ensure minimal interference among channels.
d. Electrode Placement & Type:
   Followed standard placement protocols (e.g., 10–20 system for EEG, Lead II for ECG).
   Used medical-grade Ag/AgCl electrodes; ensure consistent skin prep.
e. Environmental Artifacts: Used real-world settings in lab environment.
f. Sampling Rate:
   ECG: ≥ 125 Hz
   EMG: ≥ 500 Hz
   EEG: ≥ 256 Hz
   EOG: ≥ 75 Hz
g. Impedance Monitoring: Maintained electrode-skin impedance < 5 kΩ.
h. Duration: Recorded for varying durations (1 min to 5 min) under controlled and

uncontrolled conditions.

4.5.6.2 Acquiring of ECG Signals

The ECG signal is a crucial representation of the heart's electrical activity, providing valuable insights into cardiac health and function. The ECG waveform consists of distinct components, including the P wave, QRS complex, and T wave, each component refers to specific phases of the heart's electrical cycle. The P wave represents atrial depolarization, the QRS complex indicates ventricular depolarization, and the T wave reflects ventricular repolarization. Abnormalities in the ECG waveform, such as irregular intervals, missing waves, or unusual amplitudes, can signal arrhythmias, myocardial infarction, or other heart conditions. By analyzing ECG signals, healthcare professionals can diagnose and monitor cardiovascular diseases, enabling early intervention and effective treatment.

To evaluate the performance of our developed prototype in acquiring ECG signals, we used Ag/AgCl surface electrodes on human subjects. We specifically acquired Lead-II ECG signals at a sampling rate of 125 Hz, with data acquisition conducted at a baud rate of 115200. The signals were initially recorded without applying digital ECG filters and as well as using a digital ECG filter to assess its effectiveness in noise reduction and signal enhancement.

To further analyze the filtering performance, we plotted the frequency response curve of the digital ECG filter, which is a 4th-order IIR (Infinite Impulse Response) filter, as shown in Fig. 4.16. This frequency response characterization was crucial in validating the filter's ability to effectively remove unwanted noise and baseline wander while preserving the essential ECG components.

For visualization and comparative analysis, we used 'LabChart' software (developed by M/s AD Instruments) to plot both the raw ECG signals and the filtered signals. The test setup for ECG signal acquisition is illustrated in Fig. 4.17, while Fig. 4.18 presents a comparative view of the raw and filtered signals acquired by the prototype. The results confirmed that the developed prototype successfully captured ECG signals with improved signal clarity and noise rejection after digital filtering, demonstrating its potential for accurate biopotential signal acquisition in biomedical applications.

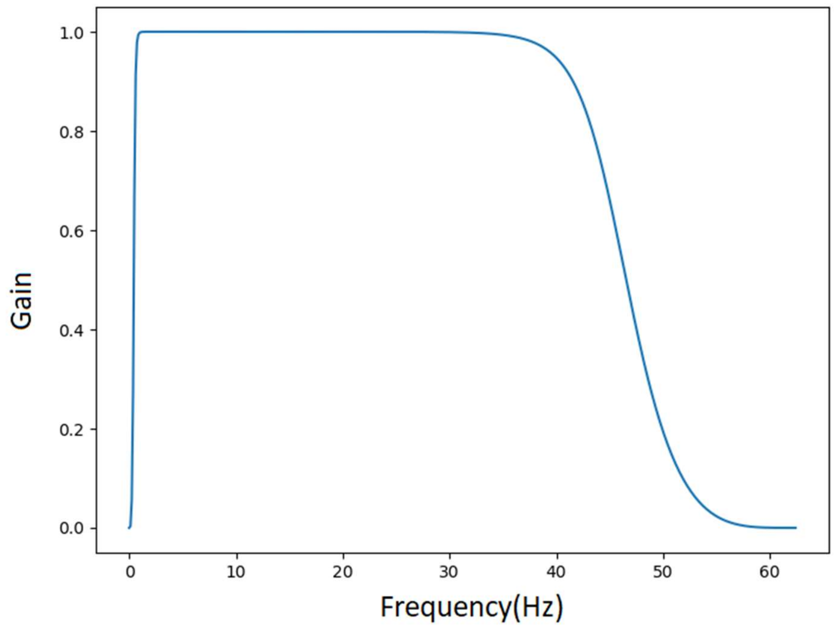


Figure 4.16 Frequency response of ECG filter.

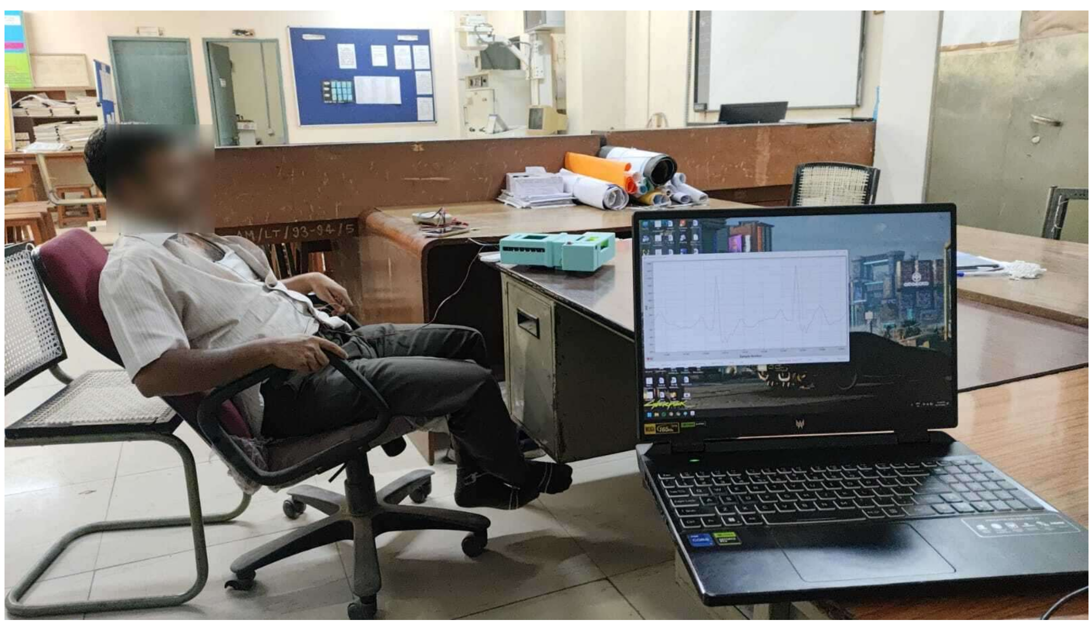


Figure 4.17 Acquisition of real-life ECG signals by the system.

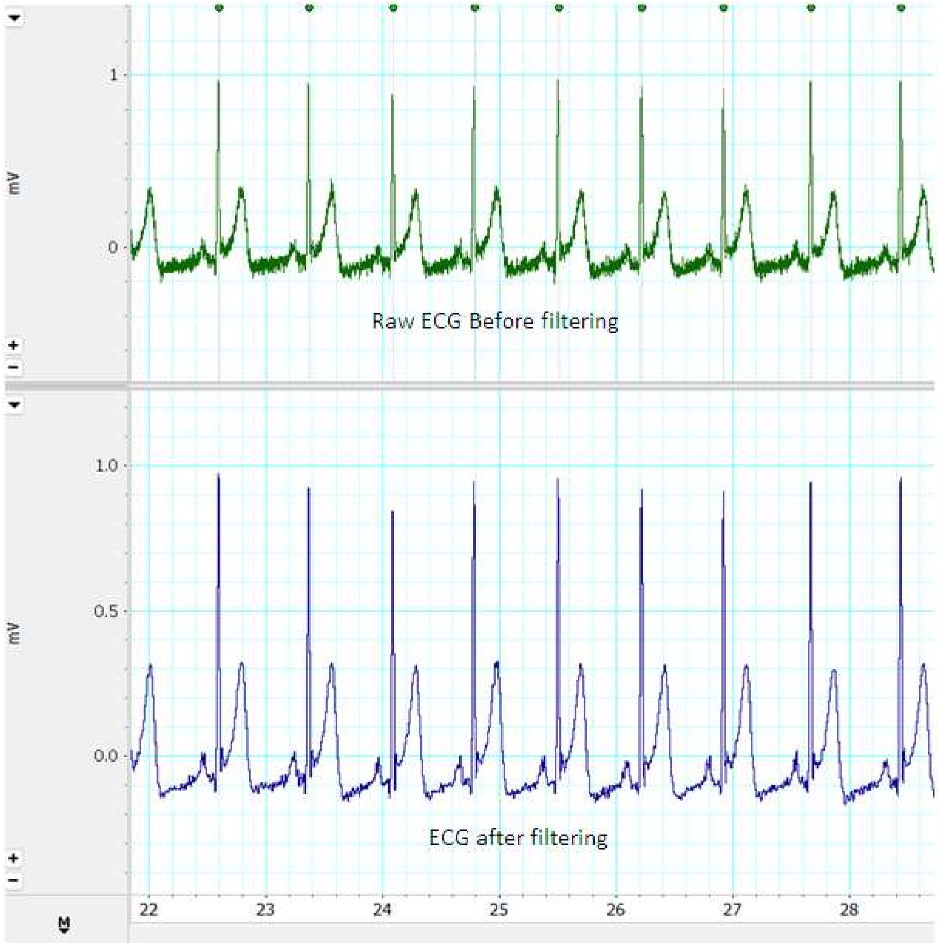


Figure 4.18 Raw and filtered real life ECG signal acquisition by the system.

4.5.6.3 Acquiring of EMG Signals

The EMG signal is essential for analyzing muscle activity and neuromuscular function, as it captures the electrical impulses generated during muscle contraction. The EMG waveform consists of amplitude variations and frequency components that reflect muscle strength, fatigue, and coordination. A higher amplitude indicates stronger muscle activation, while changes in frequency patterns can signal muscle fatigue or neurological disorders. By studying the EMG waveform, healthcare professionals and researchers can diagnose neuromuscular diseases, assess muscle rehabilitation progress, and optimize prosthetic control. Its significance extends to sports science, ergonomics, and biofeedback therapy, making EMG a powerful tool for understanding and improving muscle function.

To evaluate the performance of the developed system in acquiring EMG signals, we conducted tests on human subjects by placing Ag/AgCl surface electrodes over the intrinsic hand muscles. The signals were acquired at a sampling rate of 500 Hz, ensuring high temporal resolution for capturing muscle activity.

To assess the effectiveness of the digital filtering process, we plotted the frequency response curve of the 4th-order IIR (Infinite Impulse Response) EMG filter, as illustrated in Fig.

4.19. This analysis was essential to validate the filter's capability in eliminating unwanted noise and baseline wander while preserving the critical EMG signal components necessary for accurate neuromuscular assessment. The test setup for EMG signal acquisition is illustrated in Fig. 4.20

The acquired EMG signal, after filtering, is presented in Fig. 4.21, demonstrating a clear reduction in noise and an enhancement of signal quality. These results confirm that the developed prototype successfully captured EMG signals, exhibiting improved clarity and noise rejection through digital filtering. The system's ability to accurately record EMG data highlights its potential for clinical and research applications in neuromuscular studies, rehabilitation, and prosthetics control.

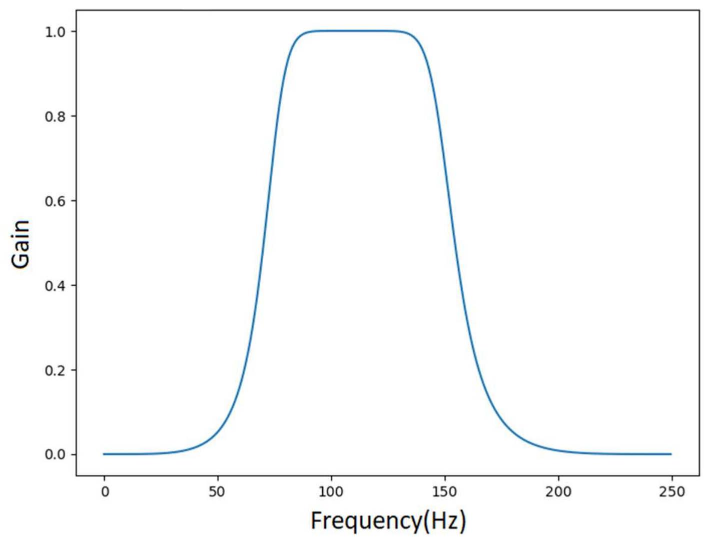


Figure 4.19 Frequency response of EMG filter.

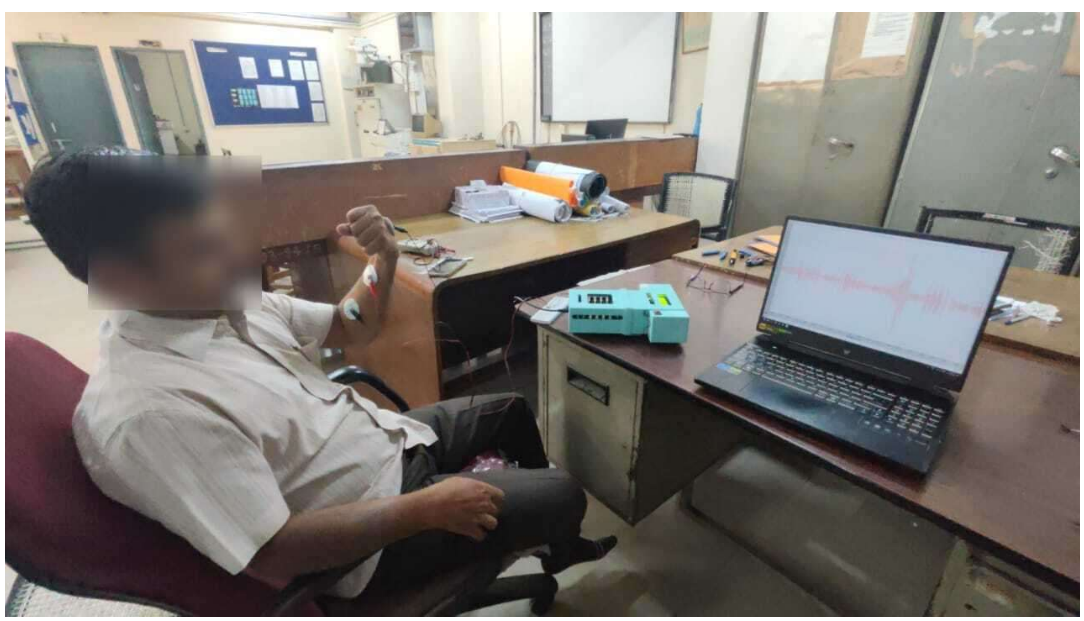


Figure 4.20 Acquisition of real-life EMG signals by the system.

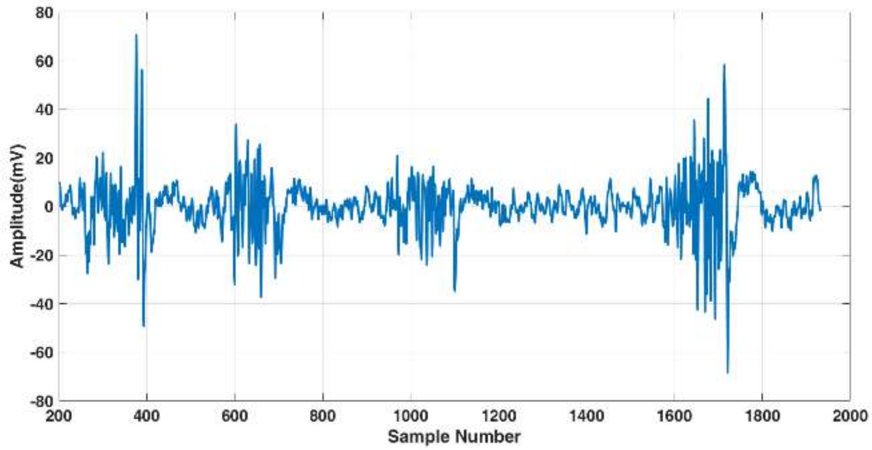


Figure 4.21 Real-life EMG signal acquisition by the system.

4.5.6.4 Acquiring of EOG Signals

The EOG (Electrooculography) signal is crucial for tracking eye movements and assessing ocular activity, making it valuable in medical, neurological, and human-computer interaction applications. The EOG waveform represents voltage changes generated by the movement of the eyeball, with distinct patterns corresponding to horizontal and vertical eye motions. By analyzing these waveforms, researchers and clinicians can detect eye movement disorders, monitor sleep stages (REM detection), and assist in diagnosing neurological conditions like Parkinson's disease. Additionally, EOG signals are widely used in assistive technologies, such as eye-tracking systems for individuals with disabilities, enhancing their ability to communicate and interact with their environment.

To evaluate the performance of the developed system in acquiring EOG (Electrooculography) signals, we conducted tests on human subjects using Ag/AgCl surface electrodes. The signals were recorded at a sampling rate of 75 Hz, enabling the monitoring of both horizontal and vertical eye movements, including blinking and pupil motion.

To further assess the filtering performance, we analyzed the frequency response curve of the 4th-order IIR (Infinite Impulse Response) EOG filter, as illustrated in Fig. 4.22. This analysis was crucial in verifying the filter's ability to effectively suppress unwanted noise while preserving essential EOG signal components for accurate detection of eye movement patterns.

The test setup for acquiring EOG signals is depicted in Fig. 4.23, while the acquired EOG signal is presented in Fig. 4.24. The results confirmed that the developed prototype successfully captured EOG signals, demonstrating enhanced signal clarity and noise rejection through digital filtering. The system's ability to accurately record EOG data highlights its potential for applications in eye-tracking research, neurological assessments, assistive technologies, and human-computer interaction systems.

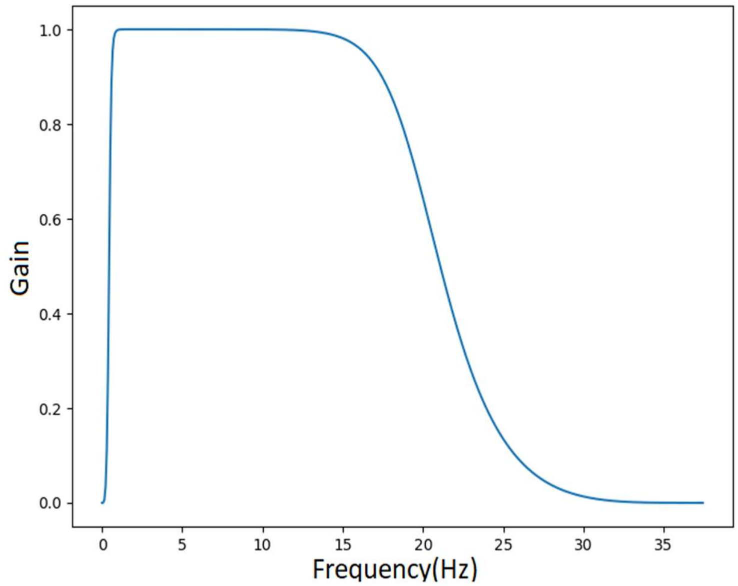


Figure 4.22 Frequency response of EOG filter.

Figure 4.23 Acquisition of real-life EOG signal by the system.

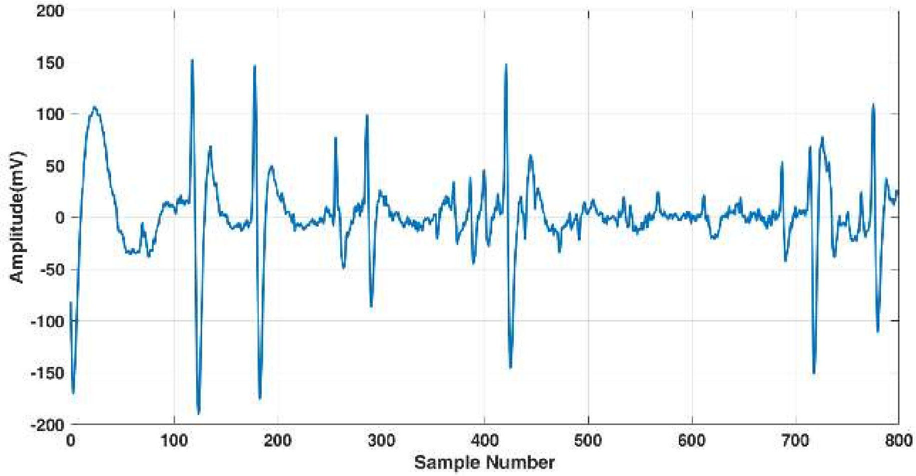


Figure 4.24 Real-life EOG signal acquisition by the system.

4.5.6.5 Acquiring of EEG Signals

The EEG (Electroencephalography) signal is essential for analyzing brain activity and neural function, providing insights into cognitive states, sleep patterns, and neurological disorders. The EEG waveform consists of different frequency bands, such as alpha, beta, and gamma, delta and theta, each associated with specific mental and physiological states. By interpreting these waveforms, clinicians can diagnose conditions like epilepsy, sleep disorders, and brain injuries, while researchers use EEG for studying cognition, attention, and mental workload. Additionally, EEG signals play a vital role in brain-computer interface (BCI) applications, enabling direct communication between the brain and external devices, thereby advancing neuro-technology and assistive systems.

To evaluate the performance of the developed system in acquiring EEG (Electroencephalography) signals, we conducted tests on human subjects using Ag/AgCl surface electrodes placed on the frontal cortex. The signals were recorded at a sampling rate of 256 Hz, ensuring high-resolution capture of neural activity.

To further assess the filtering performance, we analyzed the frequency response curve of the 4th-order IIR (Infinite Impulse Response) EEG filter, as illustrated in Fig. 4.25. This analysis was essential in validating the filter's effectiveness in eliminating noise and artefacts while preserving essential EEG components, crucial for brain signal analysis.

The acquired EEG signal is presented in Fig. 4.26. The results confirmed that the developed prototype successfully captured EEG signals, demonstrating enhanced signal clarity and noise rejection through digital filtering. The system's ability to accurately record EEG data highlights its potential for applications in neurological research, brain-computer interface (BCI) systems, cognitive studies, and clinical diagnostics.

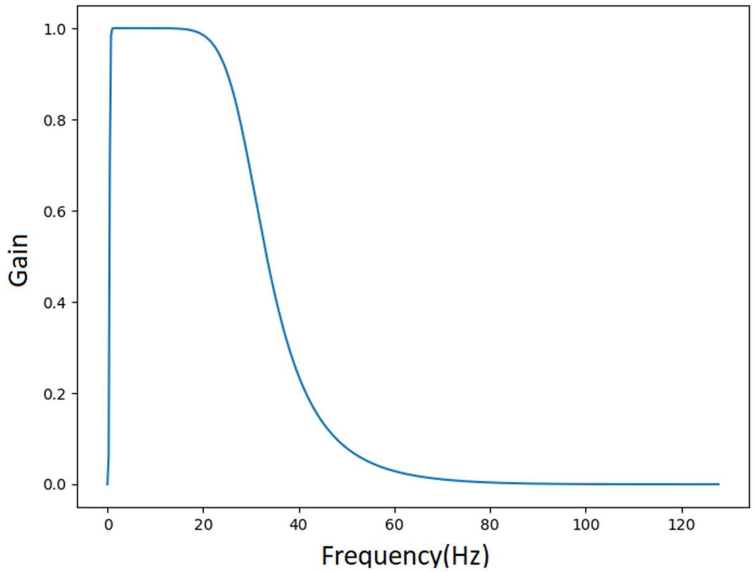


Figure 4.25 Frequency response of EEG filter.

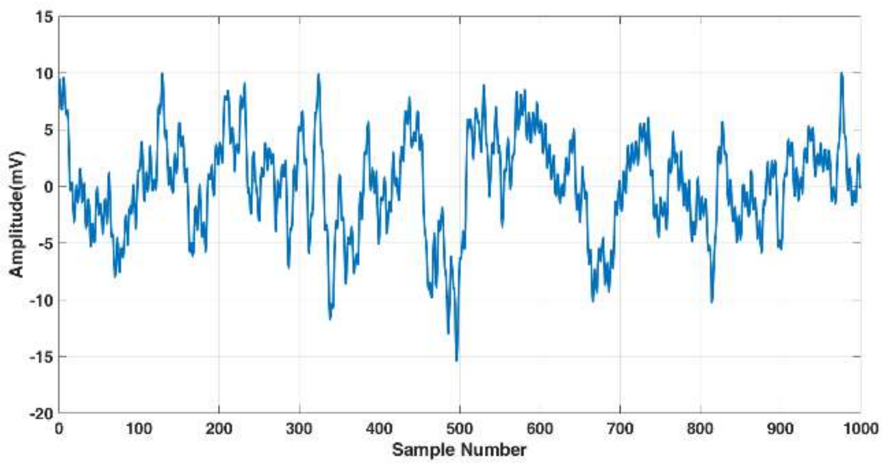


Figure 4.26 Real-life EEG signal acquisition by the system.

4.5.7. Test for Acquiring 16-channel signal simultaneously and Reconfigurability of 2-electrode and 3-electrode configurations

After successfully acquiring various biopotential signals, we proceeded to test our prototype's capability to acquire signals from all 16 channels simultaneously. In this testing phase, we also evaluated the reconfiguration ability of the system, specifically to verify whether it could effectively acquire signals from both 2-electrode and 3-electrode configurations. To test this, we configured 6 channels in a 2-electrode setup by appropriately sorting the terminals of jumpers JP2 to JP7 on the prototype PCB. For the remaining 10 channels, we retained the 3-electrode configuration by leaving the jumpers unsorted [2].

The system was then tested by applying the same ECG signal produced by the Fluke ProSim2 simulator across all channels. To visualize the signals, we used the 'TelemetryViewer' software by M/s Farrell Farahbod, which provided an intuitive user interface for monitoring multiple signals simultaneously. The test results confirmed that the system successfully acquired and displayed all 16-channel signals without distortion, operating effectively in both 2-electrode and 3-electrode configurations at the same time, as demonstrated in Fig.4.27 [2]. This successful demonstration of reconfiguration and simultaneous signal acquisition highlights the flexibility and robustness of the developed system.

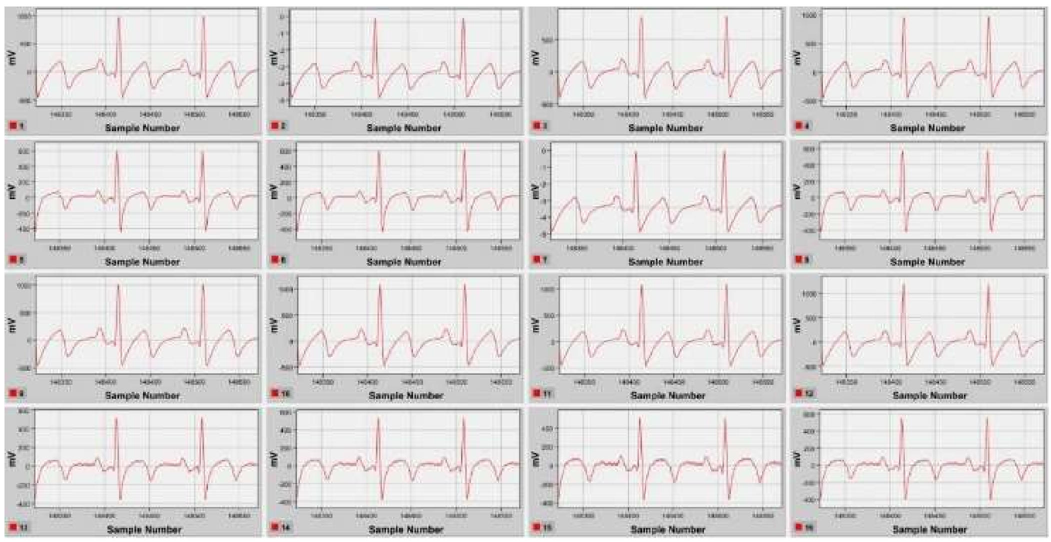


Figure 4.27 16 channel ECG signal acquisition by the system, with the same ECG input provided to all 16 channels. Six channels were configured to acquire signals using a 2-electrode setup, while the remaining ten channels used a 3-electrode configuration.

4.5.8. Power consumption and Noise amplitude Measurement

Measuring the power consumption of a Bio DAQ system is essential for evaluating energy efficiency, optimizing battery life, and ensuring overall system performance. To achieve this, we used a digital multimeter and an oscilloscope equipped with a current probe to accurately measure voltage and current. A precision 0.1Ω shunt resistor was placed in series with the power supply line to measure the voltage drop, allowing for precise current calculation. The power consumption was then determined by multiplying the measured current with the corresponding voltage, providing a reliable assessment of the system's energy requirements.

We measured the transmitter's power consumption under different operational conditions. The transmitter consumed approximately 1W during normal operation, while power usage increased to around 5W when the stimulator was in use, reflecting the additional energy requirements during stimulation.

Measuring the peak-to-peak noise amplitude is crucial for assessing the signal quality of a Bio DAQ system, as it helps to evaluate the system's vulnerability to electrical and environmental noise, ensuring precise signal acquisition. To measure internal system noise without external interference, we shorted the input terminals to ground using a 1kΩ resistor. The oscilloscope was set to AC coupling mode to isolate and analyze only the noise component. With no input signal, we observed the waveform on the oscilloscope, identifying the highest and lowest voltage points in the noise waveform. The peak-to-peak noise amplitude was then determined using the following formula.

$$VNoise = VMax - VMin$$

Where,

$$VNoise = \text{Peak to peak noise amplitude}$$

$$VMax = \text{Maximum noise voltage}$$

$$VMin = \text{Minimum noise voltage}$$

The testing revealed that the peak-to-peak noise amplitude was remarkably low, approximately 1 microvolt, indicating that the system maintained a high level of signal integrity and minimized interference, ensuring reliable performance during signal transmission.

4.6. Conclusion

The test results validate that our developed prototype effectively acquires a wide range of biopotential signals, including ECG, EMG, EOG, and EEG, with strong noise rejection capabilities under real world conditions . This demonstrates the system's ability to maintain high signal quality while minimizing interference, which is essential for accurate diagnostics and continuous monitoring.

Beyond functional testing, the prototype also underwent rigorous safety assessments to ensure compliance with medical standards. The Electrical Safety Test, conducted in accordance with IEC 60601-1 standard, confirmed that the device operates safely in medical environments, posing no electrical hazards to patients or operators. Additionally, the Electromagnetic Interference (EMI) Test, performed in compliance with CISPR 11 standard, verified the system's electromagnetic compatibility, ensuring that it functions without causing disruptive interference to other electronic devices.

Furthermore, this chapter highlights the acquisition of biopotential signals from real-life patients, showcasing the system's practical applicability and reliability in capturing high-quality signals under real-world conditions. The detailed test results offer valuable insights into the system's performance, affirming its capability to meet its intended objectives.

These findings emphasize the prototype's effectiveness, reliability, and safety, positioning it as a promising tool for clinical and diagnostic applications. This achievement strengthens the potential of the developed system for broader clinical adoption, regulatory approval, and future commercialization.

CHAPTER - 5

Conclusions and Future Perspectives

Chapter 5
Conclusions and Future Perspectives

5.1 Summary of the Thesis

The thesis aims to develop and evaluate a low-cost, wireless, compact, 16-channel Biopotential Data Acquisition (Bio DAQ) and an integrated arbitrary waveform stimulator system. The research focuses on designing a portable, power-efficient module that can sense, amplify, and transmit biopotential signals while integrating an electrical stimulator for controlled muscle stimulation.
The objectives include: Developing a Reliable Bio DAQ System – Designing a flexible system with user-selectable digital filters, configurable analog bandpass filters, and the ability to acquire different signals from multiple patients while ensuring low power consumption and real-time data transmission.
Developing an Integrated Electrical Stimulator – Creating a microcontroller-based charge-balanced trapezoidal pulse based stimulator with adjustable frequency and pulse width to enhance comfort and effectiveness while reducing adverse effects.
Testing and Evaluation – Ensuring compliance with international standards (IEC 60601-1, CISPR 11) through electrical safety, electromagnetic interference, and functional tests using simulators and real-life signals.
The research aims to address the limitations of existing systems and provide a user-friendly, cost-effective solution for long-term data acquisition and stimulation.

This thesis is structured into five chapters, each addressing a critical aspect of the development and evaluation of the wireless Bio DAQ system.

Chapter 1 establishes the foundation for the thesis by presenting an extensive description of origin of biopotential, different types of bipotential signals like EEG, ECG, EOG, EMG etc with their characteristics and significance. This chapter illustrates the biopotential data acquisition (Bio DAQ) system and limitations of the current Bio DAQ systems like most of the systems are wired systems which restrict mobility and patient comfort; designed for specific signals like EEG, EOG, ECG; not suitable for animal studies and non-availability of integrated stimulator. The chapter outlines the specific objectives of the research, which include development of wireless Bio DAQ system with user-selectable digital filters, configurable analog bandpass filters, and the ability to acquire different signals from multiple patients while ensuring low power consumption and real-time data transmission. It will also have an integrated innovative stimulator that enhances patient comfort, and ensuring safe electrical stimulation. It also describes the organization of the thesis and the rationale behind the chosen research approach.

In **Chapter 2,** we present an extensive literature review on wireless Bio DAQ system. This chapter provides a comprehensive review of the latest wireless Bio DAQ systems, covering their applications, signal acquisition methods, design methodologies, and wireless technologies. It highlights key aspects such as signal processing, noise reduction techniques, and the benefits of wireless systems over traditional wired setups. This review serves as a valuable resource to emphasize the potential of wireless Bio DAQ systems for continuous and remote physiological monitoring. The findings underscore the need for future research to improve signal processing, enhance accuracy, develop non-signal-specific Bio DAQ systems, and integrate electrical stimulators that minimize adverse effects while ensuring patient safety during prolonged use.

In **Chapter 3,** we describe the development of the circuit and subsystems for the wireless Bio DAQ system. The chapter starts with the general challenge and targeted objective of the design. This is followed by methods of development of several subsystems like Analog Front End (AFE), wireless system, Microcontroller Unit (MCU), power supply, user interface, integrated stimulator, and firmware development. It will describe the different stages of development like from initial schematic design to the final PCB layout and breadboard implementation of the circuit. We explored various circuit designs to finalize a configuration that meets our objectives.

Chapter 4 details the development of a fully functional prototype by integrating key subsystems, including the Analog Front End (AFE), Microcontroller Unit (MCU), Wireless Module, Stimulator Module, Power Supply, and Display Unit. The process begins with circuit implementation on a breadboard, followed by iterative testing, and culminates in a compact, single PCB module. The chapter covers: (1) Breadboard Testing: Ensuring individual subsystems function correctly before integration, resolving early-stage challenges. (2) PCB Integration: Optimizing layout for signal integrity, noise reduction, and reliable communication between modules. (3) Testing & Validation: Conducting electrical safety (IEC 60601-1) and electromagnetic interference (CISPR 11) tests as per international standards, along with real-life biopotential signal acquisition to confirm system reliability. The results validate the prototype’s effectiveness, demonstrating its capability to acquire high-quality biopotential signals and meet its intended objectives.

Chapter 5 summarizes the key findings of the research and discusses their implications. It highlights the contributions of the thesis to the field of wireless Bio DAQ technology, including advancements in flexibility approach and reconfigurability in circuit design, development of new integrated stimulators, enhancing safety and user comfort. The chapter also outlines potential directions for future research, suggesting areas for further development to enhance the system's capabilities and broaden its applicability. This concluding chapter emphasizes the significant progress made and sets the stage for continued innovation in wireless Bio DAQ technology.

5.2 Conclusions

In this research, we have successfully designed and developed a wireless, compact, 16-channel Biopotential Data Acquisition (Bio DAQ) system integrated with an innovative arbitrary waveform stimulator. This system addresses multiple challenges identified in existing Bio DAQ technologies, including the discomfort associated with wired systems, limitations in signal acquisition flexibility, and the absence of an integrated stimulator that ensures safe and effective electrical stimulation.

Our work began with a thorough review of existing Bio DAQ systems, identifying key limitations such as their restriction to specific biosignals, lack of adaptability for multi-signal acquisition, and the potential risks posed by non-charge-balanced stimulation. To overcome these challenges, we set clear objectives focused on enhancing patient comfort, improving noise rejection, extending transmission range, and ensuring safe electrical stimulation with user-selectable parameters.

One of the most significant innovations of the developed prototype is its reconfigurability, allowing simultaneous recording of physiological signals from up to four patients without requiring hardware modifications. This makes the system highly adaptable for clinical and research applications, where different biopotential signals - such as EEG, EOG, ECG, and EMG can be acquired from multiple subjects in real time.

Another unique feature is the integration of an arbitrary waveform stimulator, a key advancement over conventional devices that primarily use symmetrical or asymmetrical square pulses. Unlike traditional systems that rely on transformers and MOSFET-based switching, our stimulator generates charge-balanced trapezoidal waveforms. This design ensures true charge neutrality, preventing net DC current delivery to tissues, which could otherwise lead to adverse physiological effects. The trapezoidal waveform, with its smooth ramp-up and ramp-down phases, enhances stimulation comfort, reduces sudden muscle contractions, and provides more effective neuromuscular activation.

The developed stimulator operates within a frequency range of 0 Hz to 50 Hz, supports a pulse width of up to 300 microseconds, and delivers a peak-to-peak voltage of 70 volts, making it suitable for a wide range of biomedical applications, including rehabilitation, prosthetics, and neuromuscular research.

Most commercially available systems are tailored for specific signals such as EMG, ECG, or EEG. The amplifier gains and filter frequencies in these systems are optimized for the targeted signals, making it challenging to use a single device for acquiring other types of signals. For example, the device and amplifier is specifically designed for acquiring ECG signals cannot be used for acquiring EMG signals. This restricts the versatility of the system.

To address this challenge, we have developed an innovative hardware filters along with user-selectable digital filters for each channel, specific to signal frequencies such as EMG, EOG, ECG, and EEG. This flexibility allows the same system to simultaneously acquire multiple signals, such as EMG alongside ECG or EOG, ensuring versatility in various applications. These filters enable real-time signal processing, significantly reducing motion artifacts and electrical noise, thereby improving signal clarity for accurate diagnostics. The system's exceptional noise reduction capabilities, achieving noise levels as low as 1 microvolt, further enhance its reliability and performance.

To validate the functionality and robustness of the prototype, extensive functional and safety tests were conducted. Various functional tests from both simulator as well as real life signals confirm that our developed Bio DAQ system successfully acquires various types of biopotential signals with robust noise rejection capabilities. This indicates that the system is effective in maintaining signal quality while minimizing interference, which is crucial for accurate diagnostics and monitoring. In addition to functional testing, the prototype underwent rigorous safety tests to ensure it meets medical standards. The Electrical Safety Test, conducted according to IEC 60601-1 standard, evaluated the device's safety in medical environments, ensuring that it poses no electrical hazards during operation. Furthermore, the Electromagnetic Interference (EMI) Test, in compliance with CISPR 11 standard, assessed the system's electromagnetic compatibility, confirming that it operates without causing harmful interference to other devices.

In summary, this research has successfully contributed to the advancement of wireless Bio DAQ technology, offering an adaptable, multi-channel, and noise-resistant solution with an integrated charge-balanced stimulator. The system's performance, validated through rigorous testing, ensures its safety, efficiency, and usability for various biomedical applications. By overcoming existing limitations and introducing novel features, this work paves the way for further innovations in biomedical signal acquisition, stimulation, and real-time patient monitoring.

5.3 Future Perspectives

The advancements achieved in this study lay a strong foundation for the next generation of Bio DAQ systems, incorporating enhanced capabilities to meet evolving biomedical and clinical needs. Our system's modular and reconfigurable architecture provides a scalable platform that can be adapted for various applications. While the current system addresses many limitations of traditional devices, there remains significant potential for further refinement and expansion. Future enhancements may include the integration of AI-driven signal analysis for automated anomaly detection, cloud-based remote monitoring for real-time patient tracking, and biofeedback-enabled systems to optimize medical diagnostics and therapeutic interventions.

Furthermore, although transitioning from wired to wireless systems has greatly enhanced patient comfort, there remains potential for further improvements. Future research could explore the development of more efficient wireless communication protocols and advanced battery management strategies to prolong operational duration and minimize the need for frequent recharging. Additionally, optimizing the ergonomic design and selecting superior materials for the Bio DAQ system could further improve user comfort and overall usability.

Additionally, the developed system holds immense potential for a wide range of clinical and research applications, particularly in neuromuscular stimulation and rehabilitation. The system can be utilized for functional electrical stimulation (FES) to restore movement in individuals with motor impairments, supporting rehabilitation therapies for stroke and spinal cord injury patients.

An essential area for future research is the advancement of stimulation waveforms and enhanced safety mechanisms. While biphasic, charge-balanced, trapezoidal waveforms have demonstrated improved safety and effectiveness, further exploration of alternative waveform designs and modulation strategies could help minimize potential physiological side effects and optimize therapeutic outcomes. Additionally, integrating real-time monitoring with adaptive control systems could enable dynamic adjustments of stimulation parameters based on patient feedback and physiological responses, ensuring more precise and personalized treatment.

Another area will be in advancement of wearable health monitoring and prosthetics. With its compact, wireless design and low power consumption, the system is well-suited for long-term biopotential signal monitoring in wearable devices, aiding in real-time health assessments and control of neuroprosthetic limbs.

Another aspect will be in multi-subject biopotential signal studies. The ability to simultaneously record physiological signals from multiple subjects makes this system ideal for large-scale research studies in neuroscience, sleep analysis, and psychophysiology.

Future perspective includes conducting clinical trials on a larger and more diverse patient cohort for gaining a comprehensive understanding of the system's effectiveness across various conditions and demographics. Testing the Bio DAQ system on a broader range of patients will provide valuable insights into its performance and potential benefits for different medical conditions.

These capabilities pave the way for further research and development, ensuring that wireless Bio DAQ technology continues to evolve to meet the growing demands of modern healthcare and scientific exploration.

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APPENDIX

Table A-1. Bill of Material (BOM) and Specification of Components Used in Prototype PCB

Sl No	Quantity	Value	Device	Package	Description
1	1	1-825433-6	1-825433-6	PINHD-1X16 (2.54mm)	Connector Header Through Hole 16 position 0.100" (2.54mm), MALE
2	1	PPTC042LFBN-RC	PPTC042LFBN-RC	FE04-2 (2.54 mm)	8 Position Header Connector 0.100" (2.54mm) Through Hole Tin, FEMALE
3	1	PH1-06-UA	PH1-06-UA	PINHD-1X6 (2.54 mm)	Connector Header Through Hole 6 position 0.100" (2.54mm), MALE
4	1	220 ohms	CF14JT220R	CF14JT220RCT-ND/ CF14JT220RTR-ND	220 Ohms ±5% 0.25W, 1/4W Through Hole Resistor Axial Flame Retardant Coating, Safety Carbon Film
5	1	10k ohm	TRIMMER	PT10LV10-103A2020-S	WCAP-CSMH MLCCs
6	2	DS01C-254-S-08BE	DS01C-254-S-08BE	DIP SWITCH, SPST, 2.54 PITCH, RA	Dip Switch SPST 8 Position Through Hole Slide (Standard) Actuator 25mA 24VDC
7	3	SLW-121586-5A-D	SLW-121586-5A-D	SWITCH SLIDE SPDT 0.5A 50V	SWITCH SLIDE SPDT 0.5A 50V
8	5	PPPC021LFBN-RC	PPPC021LFBN-RC	FE02-1 (2.54mm)	2 Position Receptacle Connector Through Hole (FEMALE)
9	5	430186070716	430186070716	Bulk	SWITCH TACTILE SPST-NO 0.05A 12V
10	8	220k ohm	CRGP0603F220K	0603_1.6X0.8X0.45(LXWXH)	Thick Film Resistors
11	9	PPTC081LFBN-RC	PPTC081LFBN-RC	FE08-1 (2.54 mm), TRAY	CONN HDR 8POS 0.1 TIN PCB, FEMALE
12	8	PH1-08-UA	PH1-08-UA	PINHD-1X8 (2.54mm)	Connector Header Through Hole 8 position 0.100" (2.54mm), MALE
13	16	TL084CPW	TL084CPW	TSSOP-14	GENERAL PURPOSE J-FET QUAD OPERATIONAL AMPLIFIERS
14	16	100nF	C0603C104J4RAC7040	WCAP-CSMH_0603_W	WCAP-CSMH MLCCs
15	16	2.2nF	C1608CH2E222J080AA	WCAP-CSMH_0603_W	WCAP-CSMH MLCCs
16	16	220nF	CC0603JRX7R9BB224	WCAP-CSMH_0603_W	WCAP-CSMH MLCCs
17	16	4.7uF	GRM188R6YA475KE15D	WCAP-CSMH_0603_W	WCAP-CSMH MLCCs
18	16	47uF	GRM188R60J476ME01D	WCAP-CSMH_0603_W	WCAP-CSMH MLCCs

19	16	220k ohm	TRIMMER	PT10MV10-224A2020-S	Trimmer Resistors - 200 kOhms 0.15W PC Pins Through Hole Trimmer Potentiometer Carbon 1.0 Turn Top Adjustment
20	20	694106301002	694106301002	Bulk	CONN PWR JACK 2.1X5.5MM SOLDER
21	32	47nF	C0603X473J1REC7411	WCAP-CSMH_0603_W	WCAP-CSMH MLCCs
22	33	PH1-02-UA	PH1-02-UA	CONN HEADER VERT 2POS 2.54MM	Connector Header Through Hole 2 position 0.100" (2.54mm), MALE
23	48	1M ohm	CRGP0603F1M0	0603_1.6X0.8X0.45(LXWXH)	Thick Film Resistors
24	64	1k ohm	CRGP0603F1K0	0603_1.6X0.8X0.45(LXWXH)	Thick Film Resistors
25	64	10k ohm	CRGP0603F10K	0603_1.6X0.8X0.45(LXWXH)	Thick Film Resistors
26	45	DNP	Only footprint to be printed in PCB. No component will be mounted at these places		Only footprint to be printed in PCB. No component will be mounted at these places
27	1	ARDUINO MEGA 2560 REV3	ARDUINO MEGA 2560 REV3		Arduino MEGA microcontroller development board
28	1	ESP8266	ESP8266		ESP 8266 Wi-Fi module
29	2	3.7V Li-Ion Battery	3.7V Li-Ion Battery		3.7V Li-Ion Rechargeable Battery
30	1	TP5100	TP5100		2 A switch down 8.4 V / 4.2 V battery charging chip
31	1	SPST Rocker switch	SPST Rocker switch		KCD1 12V-24V ON-OFF,2 PIN Rocker Switch

Table A-2. Bill of Material (BOM) and Specification of Components Used in Stimulator PCB

Sl No	Quantity	Value	Device	Package	Description
1	1	1N5824_C508482	1N5824	DO-201AD_BD5.3-L9.5-P13.50-D1.4-RD	Schottky diode, 40V, 3A
2	1	33uH	PSPHAQ127-330M	IND-SMD_L12.0-W12.0_CDRH125L125NP-470MC	Power Inductor
3	1	47uH	CKST0605-47uH/M	IND-SMD_L7.5-W6.6	Power Inductor

4	1	LED	2A5G3HD01 LED	LED-SMD_L5.0-W2.7-FD	Light Emitting Diode
5	1	ESP32-WROOM-32-30Pin		ESP32-WROOM-32-30PIN	Microcontroller development module
6	1	PNP		TO-39-3	PNP Transistor
7	1	XL6009	XL6009	TO-263-5	DC-DC boost (step-up) converter IC
8	1	LM324	LM324L-D14-T	PDIP-14_L19.7-W6.6-P2.54-LS8.3-BL	Operational Amplifier IC
9	1	AD620	AD620SQ/883B	DIP-8_L10.0-W6.5-P2.54-LS7.6-BL	Instrumentation Amplifier IC
10	1	MPU6050	New SchematicLib	MPU6050	3-axis gyroscope and a 3-axis accelerometer
11	1	03962A		ZARYADKA_03962A	lithium battery charger module
12	1	OPA452FAKTWTG3	OPA452FAKTWTG3	TO-263-7_L10.2-W8.6-P1.27-LS14.4-TL	High voltage operational amplifier
13	1	47uF	RVT47UF50V67RV0029	CAP-SMD_BD6.3-L6.6-W6.6-LS7.6-FD	50V Electrolytic capacitor
14	2	1uF	0603X105K160NT	C0603	50V Electrolytic capacitor
15	1	100nF	CT41G-0603-2X1-50V-0.1µF-K(N)	C0603	50V Electrolytic capacitor
16	1	10nF	CT41G-0603-2X1-50V-0.01µF-K(N)	C0603	50V Electrolytic capacitor
17	1	220uF	SHG220UF50V01EC1210	CAP-TH_BD10.0-P5.00-D1.0-FD	50V Electrolytic capacitor
18	1	1000uF	50ZLJ1000M12.5X30	CAP-TH_BD12.5-P5.00-D0.8-FD	50V Electrolytic capacitor
19	1	MBR745	MBR745	ITO-220AC_L10.2-W4.5-P5.10	45V Schottky diode
20	6	Header-Male-2.54_1x2	826629-2	HDR-TH_2P-P2.54-V-M-1	2-pin male header connector with a 2.54mm pitch
21	2	Male Header	2.54-1*5P	HDR-TH_5P-P2.54-V-F	5-pin, through-hole, vertical male header with a 2.54mm pitch
22	1	12 MALE Header	P125-1112A0BASYA1	H12-2.54	12-pin header connector with a 2.54mm pitch
23	1	NPN		TO-39-3	NPN Transistor

		Transistor			
24	1	40kΩ	SCR0603F40K	R0603	Surface-mount resistor in an 0603 package
25	1	470Ω	ERJU3RD4700V	R0603	Surface-mount resistor in an 0603 package
26	1	69.8kΩ	SCR0603F69K8	R0603	Surface-mount resistor in an 0603 package
27	1	137kΩ	AC0603FR-07137KL	R0603	Surface-mount resistor in an 0603 package
28	1	37.4kΩ	MCR03EZPFX3742	R0603	Surface-mount resistor in an 0603 package
29	1	1.82K	RCT031K82FLF	R0603	Surface-mount resistor in an 0603 package
30	5	2kΩ	RMC 0603 2K J N	R0603	Surface-mount resistor in an 0603 package
31	1	47kΩ	PTFR0603B47K0N9	R0603	Surface-mount resistor in an 0603 package
32	1	220Ω	PTFR0603B220RP9	R0603	Surface-mount resistor in an 0603 package
33	1	LT1074HVCT7#PBF	LT1074HVCT7#PBF	TO-220-7-L10.5-W4.5-P1.27-BL	45V switching regulator IC
34	1	L7805CV	L7805CV	TO-220-3_L10.0-W4.5-P2.54-L	5V switching regulator IC
35	1	L7905CV	L7905CV	TO-220-3_L10.0-W4.5-P2.54-T	-5V switching regulator IC